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МЕЖДИСЦИПЛИНАРНЫЙ НАУЧНЫЙ И ПРИКЛАДНОЙ ЖУРНАЛ ПО ПРОБЛЕМАМ ПОЗНАНИЯ И СОХРАНЕНИЯ БИОСФЕРЫ И ИСПОЛЬЗОВАНИЯ ЕЕ РЕСУРСОВ

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Редакционная статья

ДЕСЯТЬ ЛЕТ ЖИЗНИ ЖУРНАЛА «БИОСФЕРА» В УСЛОВИЯХ РОСТА ЗАГРЯЗНЕННОСТИ ИНФОРМАЦИОННОЙ СРЕДЫ

В последнем номере юбилейного десятого тома журнала «Биосфера» уместно подвести итоги его десятилетнего существования.

Начнем с конца. В редакционной статье к последнему номеру годичной давности [2] отмечено катастрофическое падение качества рукописей, поступающих в журнал, но обещано не снижать планку допуска к печати несмотря ни на что. «Делай, что должно, и будь что будет». Вот и сбылось, что сбылось. Тенденция 2017 г. продолжилась, и в 2018 г. признаны негодными 50% и более поступлений к первому, второму и третьему номерам. Из двух десятков рукописей, накопившихся к четвертому номеру, до публикации можно было довести две. Отсюда и запоздалый выход номера в печать. Два десятка – это не считая запросов «сколько стоит публикация и как быстро будет опубликована»? Число таких запросов возрастает к концу года, когда все, кто «чистит себя»[1] под Минобрнауки и РАН, начинают задумываться об отчетности по статьям. Узнав, что плату с авторов журнал «Биосфера» деньгами не берет, но потратить надо будет время и силы для доведения рукописи до соответствия требованиям [2], авторы запросов интерес к журналу теряют.

С учетом того, что за деньги сейчас все равно можно опубликовать что угодно (см. рис. 1), получается, что у наших «научных работников» деньги вроде как есть, только вот времени нет. На что тогда оно уходит, если результаты работы и их оформление сплошь и рядом не выдерживают критики? При этом надо заметить, что в правилах «Биосферы»[2] нет ничего из ряда вон выходящего. Они основаны на международных стандартах для научных публикаций в сочетании с более чем толерантным отношением к техническим сторонам оформления рукописей. Но будь оно не таким, а иным, какое принято у «ведущих международных индексированных», мало кто из авторов прошел бы свою часть пути до публикации своей работы.

Таков итог. Теперь посмотрим, как к нему пришли и куда идти дальше.

Издание журнала «Биосфера», задуманное по идее проф. Э.И. Слепяна, который и стал его главным редактором, было начато Фондом научных исследований «XXI век» в 2009 г. В те времена открытый доступ к научным публикациям считался эксцентричным экспериментом, Scopus и Web of Science – удобными, хотя и не общедоступными средствами поиска нужных статей, а обоюдно слепое рецензирование – опасной формой неуважения к авторитетам.

Идею создать единую информационную платформу для специалистов в самых разных аспектах общего для всех дела по изучению и охране окружающей среды – от естественных до гуманитарных наук и от самой абстрактной теории до самой конкретной практики [4, 5] – поддержали своим согласием войти в редколлегию «Биосферы» крупнейшие ученые, в том числе академики РАН и руководители ведущих институтов (рис. 2).

Первые два номера «Биосферы» вышли в конце 2009 г. В 2012 г. журнал был включен в «Перечень рецензируемых научных изданий, в которых должны быть опубликованы основные научные результаты диссертаций на соискание ученой степени кандидата наук, на соискание ученой степени доктора наук» («Список ВАК»)[3] и остается в нем по сей день после всех пересмотров. О динамике журнала можно судить по рейтингу, основанному на интегральном показателе Science Index в eLibrary[4] для изданий по тематике «Экология человека, охрана окружающей среды» (рис. 3).

Как видно, начав с предпоследнего из 38 мест в 2010 г., журнал за два года поднялся до 10-го из 48 и далее оставался примерно на этом уровне, побывав на 4-м месте в 2014 г. (рис. 3).

В том же 2012 г., когда журнал «Биосфера» вышел на свой уровень, произошло знаковое для российской науки и научной периодики событие. Был опубликован Указ Президента Российской Федерации от 7 мая 2012 г. № 599 «О мерах по реализации государственной политики в области образования и науки». В Указе было предусмотрено «увеличение к 2015 году доли публикаций российских исследователей в общем количестве публикаций в мировых научных журналах, индексируемых в базе данных “Сеть науки” (WEB of Science), до 2,44 процента»[5]. Примечательны как точ-

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[1] «Я себя под Лениным чищу, чтобы плыть в революцию дальше». В. Маяковский.

[2] См. сайт журнала: http://21bs.ru.

[3] См. комментарии на эту тему в издаваемом ФНИ «XXI век» журнале «Машины и Механизмы»: http://21mm.ru/news/nauka/chto-takoe-spisokvak-/

[4] https://elibrary.ru/titles_compare.asp

[5] https://rg.ru/2012/05/09/nauka-dok.html

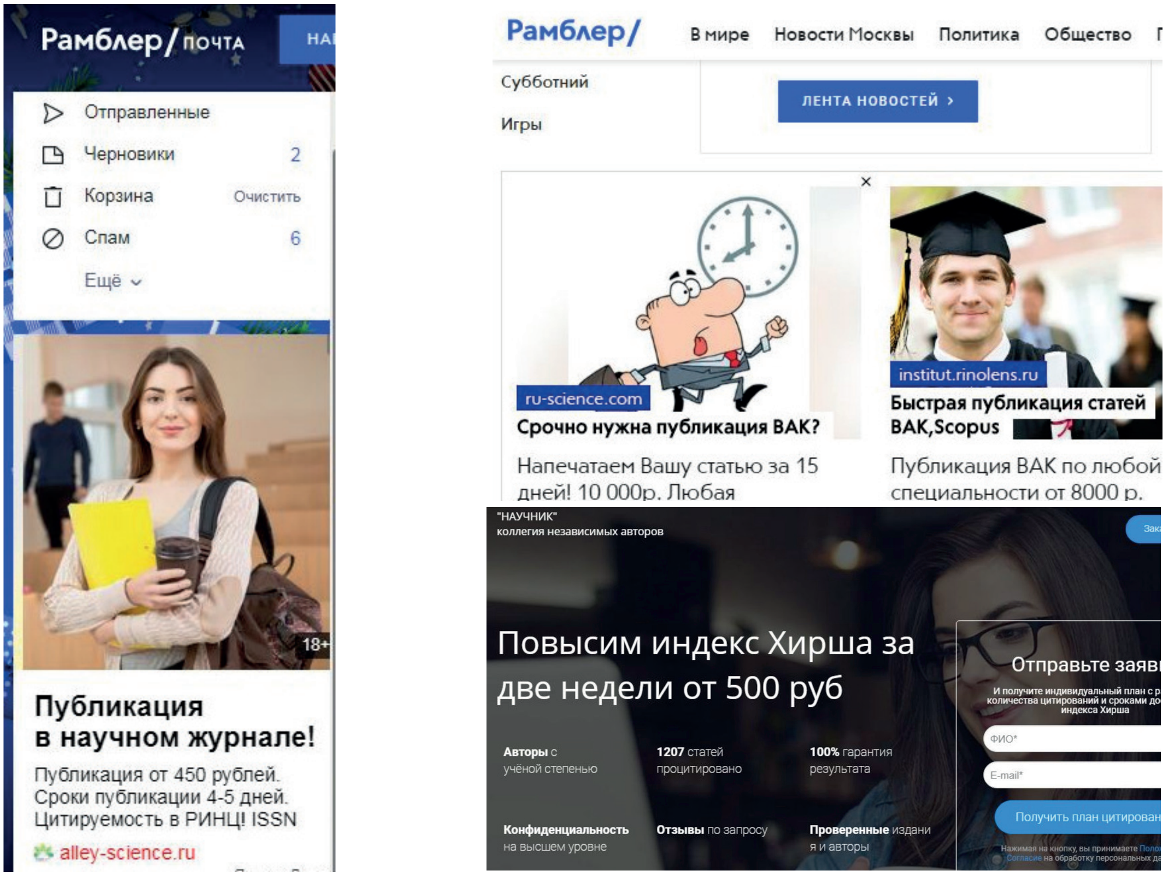

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Рис. 1. Вот так выглядит поллюция информационной среды. На электронную почту членов редколлегии, засветившихся, само собой, в сети запросами по научным публикациям, предложения опубликоваться в «журналах списка ВАК», в «журналах, индексированных в Scopus» и т. п. приходят ворохами. Из того, что поток предложений платных услуг такого рода не убывает, следует, что они пользуются неубывающим спросом. Собственно, именно порочный спрос порождает порочные предложения, а сам не может быть порожден ничем иным, кроме порочной политики. Конкретику можно найти, например, на сайте https://www.kommersant.ru/doc/3035895

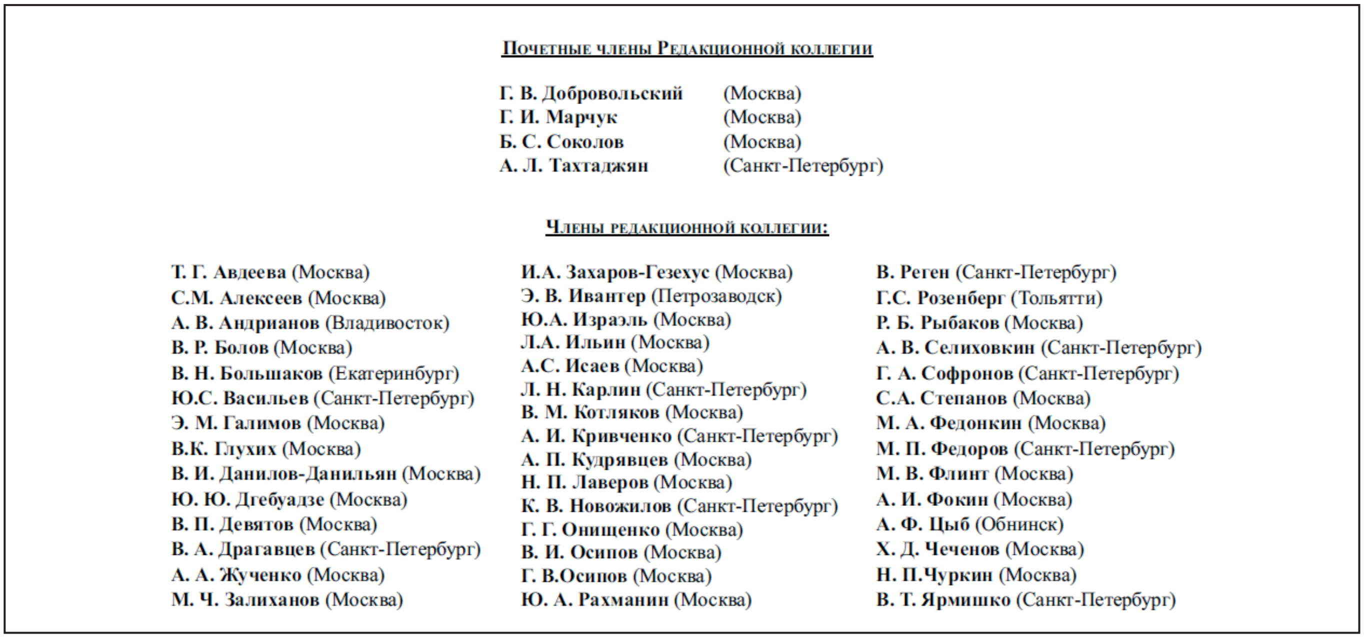

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Рис. 2. Фрагмент титульного листа первого номера журнала «Биосфера»

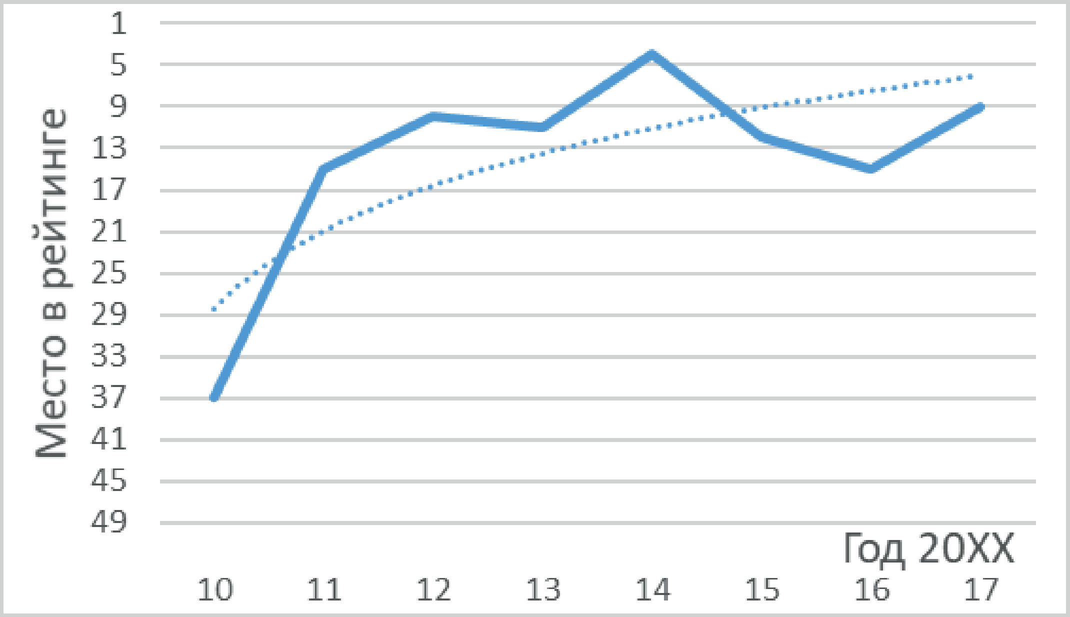
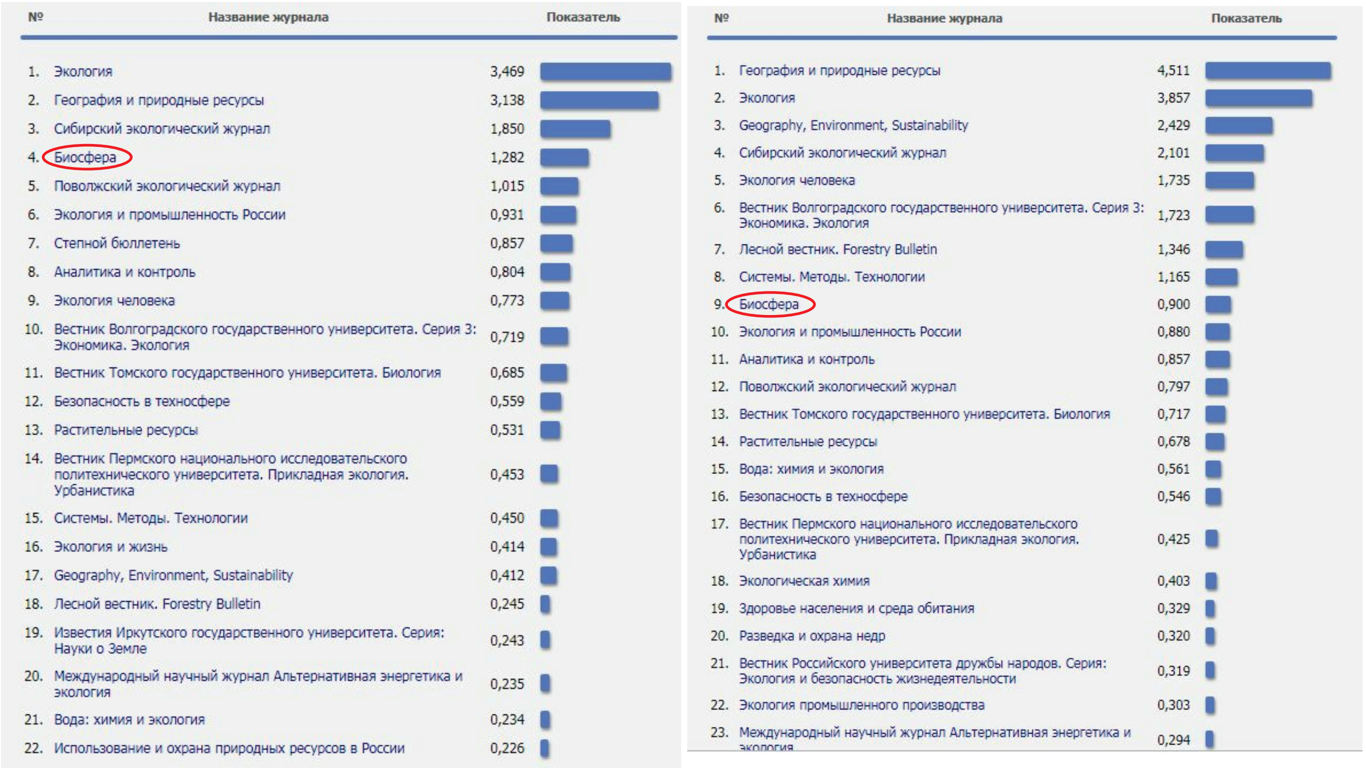


Рис. 3. Динамика рейтинга журнала «Биосфера» по Science Index среди журналов по экологии человека и охране среды. Пунктиром обозначен тренд



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9.	Экология человека	0,773
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16.	Экология и жизнь	0,414
17.	Geography, Environment, Sustainability	0,412
18.	Лесной вестник. Forestry Bulletin	0,245
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21.	Вестник Российского университета дружбы народов. Серия: Экология и безопасность жизнедеятельности	0,319
22.	Экология промышленного производства	0,303
23.	Международный научный журнал Альтернативная энергетика и экология	0,294

2017

Рис. 4. Место журнала «Биосфера» среди 48 экологических журналов в 2014 и 2017 гг.

ность целеполагания, так и сама цель. Речь шла не о повышении уровня научных исследований до такого, чтобы их результаты могли были приняты «в мировых научных журналах». Речь шла об увеличении доли публикаций в них до уровня, определенного с точностью до четвертого десятичного знака (0,0244). Но средства выполнения этой цели не были ограничены ничем, кроме как, по умолчанию, финансами на проведение исследований, результаты которых надо публиковать. Предпринятые управленцами организационные меры были основаны на материальном стимулировании попыток пробиться в «мировые научные» всеми правдами и неправдами. Комментарии, отражающие позицию научного сообщества к такой политике, можно найти в публикациях [1, 6, 7]. Цель вроде бы (с некоторыми оговорками по специальностям) была достигнута [3]. Обсуждение вопроса о том, какими способами она достигалась, и каковы реальные, а не наукометрические последствия ее достижения для российской науки, можно найти в ряде прежних публикаций в «Биосфере» [6, 7]. Остановимся сейчас на том, какова цена этих достижений для отечественной научной периодики. Разумеется, этот вопрос может волновать только тех, кто считает, что она имеет право на существование, в котором есть реальный смысл.

Между тем смысл российских научных журналов низведен до обслуживаниях тех, кому защищаться надо, но нечем. Согласно Указа 599 признано по факту, кто бы что ни говорил, что реальное значение для науки имеет только то, что можно опубликовать там – на английском. Более того, не просто там, а только в верхних квартилях рейтингов по специальностям. Только за это «научные работники» получают материальное поощрение и, более того, право на перезаключение договора с научными работодателями. Поэтому даже те российские журналы, которые допущены в Web of Science, остаются все равно за бортом. В высшие квартили входят не более четырех-пяти российских журналов, и все они по физике-математике [3]. Так что немудрено, что здесь предлагается для опубликования только то, что заведомо не годится там.

Что до журналов, которые переводятся на английский выборочно и в таком урезанном виде допущены в Web of Science и/или Scopus, то, например, один из соавторов этой статьи имел двукратный опыт знакомства с переводами его публикаций в российском журнале на английский язык силами Pleiades Publishing (по факту посредник между некоторыми российскими журналами и издательством Springer-Nature). В обоих случаях не меньше половины специальных терминов переведены неверно. Ладно, это еще можно исправить на уровне верстки, предоставляемой по такому делу. Но как быть с целыми фразами, смысл которых прямо противоположен смыслу исходного текста? Или с целыми абзацами, которые грамматически, может, и безупречны, но об их смысле невозможно догадаться, если не знать исходный текст? В исконно англоязычные ни один рецензент такое не пропустит. В данном случае автор хотя бы владеет английским, пусть не в совершенстве, но достаточно, чтобы опубликовать своими силами с два десятка статей в «ведущих индексированных» и, стало быть, для того, чтобы разглядеть вышеописанные безобразия. А как быть другим? Создается впечатление, что штатным переводчикам платят там за то, чтобы российские авторы представали перед всем миром недотепами, неспособными усмотреть противоречия в двух соседних предложениях, правильно изложить концепции, выдвинутые другими, а значит и сделать или предложить что-либо свое, достойное внимания. Во всяком случае, результат получается именно такой. Но, если уж выбирать между несовершенным английским, не искажающим смысл излагаемого, и гладким английским, в котором отсутствие смысла бьет в глаза, надо бы делать выбор в пользу первого. Но почему-то выбирают второе. Как тут не потянет в конспирологию?

К ней подталкивают и другие обстоятельства (надо понимать, что это шутки над собой, хотя на самом деле скоро станет не до шуток, см. ниже). Последнее время издательства зарубежных журналов стали относиться к чистоте английского все придирчивее. С одной стороны, можно понять их брезгливость в связи с возросшим в силу известного указа наплывом англоязычного косноязычия из России. С другой стороны, почему бы не делать на этом бизнес, вынуждая авторов прибегать к услугам платных редакторских агентств при издательствах? Но и этого вынуждения мало. Ведь есть еще и открытый – для читателя – доступ. Там планка чистоты английского ниже. Но ниже не только эта планка. Если получать деньги не с подписчиков, а с авторов, то для расширения доходной базы выгодней не повышать качество публикаций (а значит и барьер для авторов) для привлечения подписчиков, а снижать барьеры опубликования – для привлечения тех, кто за поднятие своего Хирша готов платить. Опасность открытого доступа для чистоты научной информационной среды отмечалась неоднократно [1, 7]. А необходимостью сохранения чистоты (и, соответственно, редакционных расходов на ее поддержание) оправдывается высокая плата за публикацию на правах открытого доступа в тех самых журналах первого и второго квартилей, которые только и идут сейчас у нас в зачет. Плата эта составляет от 1250 и до 5000 долларов США за одну статью. Сейчас пока еще многие такие журналы, но уже не все, сохраняют для авторов право выбора: либо открытый доступ, а значит повышенная вероятность прочтения и цитирования со всеми вытекающими, но за деньги; либо бесплатно, но тогда уж не обессудьте, если придираемся.

Однако скоро и того не будет. В сентябре 2018 г. 16 крупнейших европейских научных фондов и правительства 13 стран подписали соглашение о «Плане S» – предоставлении с 1 января 2020 г. немедленного открытого доступа к публикациям, подготовленным по результатам исследований, которые проводятся на средства этих фондов и/или государств (см. [9]). Далее предполагается убедить всех в необходимости перехода на такой режим. Идея, ко всеобщему удивлению, была поддержана Китаем[6]. Полного единодушия среди всех заинтересованных сторон по этому вопросу пока еще нет. Но доступ-то все равно уже стал открытым de facto (распространение личных копий pdf по запросам, сделанным на основании общедоступных рефератов, ResearchGate, Sci-Hub… «…кто весел, тот смеется; кто ищет, тот всегда найдет…»). Поэтому взимание платы за право опубликовать статью, а не за право ее прочитать оказывается единственным способом для мировых монополистов в сфере научных изданий сохранить свои сверхдоходы. Вопрос только в том, чтобы придумать максимально рентабельный бизнес-план перехода.

Издержки такой перспективы очевидны, но мало кого волнуют, кроме тех, на кого они обрушатся. Вот, например, мнение ученых из Бразилии (12-е место в мире по числу публикаций) [8]: «В Бразилии публикационные расходы покрываются государственными агентствами, финансирующими науку. Но при этом не предусмотрены специальные дополнительные расходы за редакционную обработку статей (*article processing charges – именно это является основным декларируемым компонентом платы, взимаемой с авторов. – Прим. от «Биосферы»*). Эти расходы изымаются из общей суммы гранта, так что авторам приходится выбирать между открытым доступом и реактивами… Без ограничений на плату за публикации открытый доступ станет недоступным для держателей некрупных грантов повсеместно». Гранты РФФИ – они что, крупные? А ведь в заявках на эти гранты надо заранее указывать число публикаций в «ведущих индексированных». Очевидная бредовость этой практики уже отмечалась [2]. Существующий План S элиминирует гибридные журналы, дающие авторам право выбора между публикациями на условиях платного неограниченного открытого доступа или бесплатного ограниченного. Вот мнение сотрудников Центра клинической эпидемиологии в Монреале (Канада) на этот счет: «Гибридные журналы – это необходимый элемент научной *экосистемы* (!!! – *Прим. от «Биосферы»*). План S потребует от междисциплинарных журналов (*«Биосфера» – именно такой*) перейти на полный открытый доступ, что отметет авторов, у которых средства для этого отсутствуют, особенно молодых исследователей и представителей недофинансируемых научных дисциплин» [10]. А какие биологические дисциплины у нас не являются недофинансируемыми?

Публиковать по принуждению свыше в англоязычных журналах наши недофинансируемые исследования о нашей природе и ее охране – это то же самое, что вывозить природные ресурсы. И за это мы же сами еще и платить должны? Такие публикации, как и любые другие выполненные за счет госбюджета, должны быть доступными в первую очередь для российских читателей на русском языке. Если это кому-то интересно там, пусть сами несут расходы на перевод с русского на английский. А если не интересно, то со своей природой мы сами должны справляться. «Помощников у нас никогда не было и не будет» (из новогоднего обращения Президента, см. http://kremlin.ru/events/president/news/59629). Называть помощниками культуртрегеров от Elsevier, организующих платные семинары, чтобы объяснять, как заслужить их покровительство, самым смышленым из туземцев, язык не поворачивается.

Это – не призыв к изоляционизму и отказу использовать то из имеющегося в международной информационной научной среде, в чем для нас есть реальный смысл. Смысла – реального – нет в том, чтобы ломиться со статьями по тематике журнала «Биосфера» в «международные индексированные». Но он есть в том, что журнал располагает сайтом на международной платформе Open Journals System, позволяющей организовать взаимодействие с международным агентством CrossRef для присвоения публикациям индекса Digital Object Identifier (DOI). Таким образом можно дополнять публикации на русском в цифровом формате переводами на английский под тем же DOI. Такие статьи учитываются в Google Scholar, так что любые ученые в мире, в том числе сугубо англоязычные, по запросам на темы, затронутые в публикациях в «Биосфере», будут выходить на них без необходимости платить огромные деньги за подписку на Scopus и Web of Science[7]. Авторам надо только ответственно относиться к названиям и рефератам своих статей,

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[6] Занимает теперь уже первое место в мире по числу публикаций (18,6%); следом идут США (17,8%); у России 10-е место (2,6%) – между Южной Кореей и Канадой [9].

[7] К слову, эта подписка для российских бюджетных научных организаций теперь наконец-то доступна за счет бюджета. Но техническая необходимость в ней сейчас не выходит за рамки отслеживания все тех же библиометрических показателей. То есть сначала держатели наукометрических ресурсов организовали спрос, а теперь окупают расходы, взимая плату за его удовлетворение. В раздувании спроса очень помогли под лозунгом «заграница нам поможет» местные поборники привлечения варягов для наведения порядка в собственном доме. Вот интересно, как они отнесутся к необходимости платить 1500 долларов и больше за право опубликоваться там, где публикация хоть и поощряется у нас прибавкой к зарплате, но прибавка-то в лучшем случае компенсирует затраты, причем задним числом. Для публикации в международных журналах за рубежом на самом деле есть и другие, причем вполне достойные стимулы. И они как действовали до Указа 599 и даже при советской власти, так и будут действовать независимо от административных перестроек в науке.

чтобы они привлекали внимание, равно как и к другим аспектам их оформления. Ну и нелишне, чтобы содержание тоже было на высоте. И, если российские авторы будут делать свое дело для себя, с уважением к себе и своей работе, а не к рейтингам, международный интерес к их статьям и их цитирование придут. Но сразу по указу, конечно, не получится.

И это – не выступление против открытого доступа к рецензируемой научной периодике. Просто надо, чтобы открытый доступ обеспечивали не те, кто делает его источником дохода для себя, а те, кто заинтересован в развитии науки и ее доступности для всех. Государство – заинтересовано?

Если открытый доступ перестанет быть платным для авторов, исчезнет стимул снижать планку качества рукописей для увеличения числа возможных плательщиков. Но самым главным фактором поддержания высокого уровня публикаций остается рецензирование «равными равных» (peer reviewing). Вот в каком деле надо бы заимствовать международный опыт, в частности, признание участия в рецензировании в качестве квалификационного критерия.

ФНИ «XXI век» предоставляет авторам открытый доступ бесплатно. Но перевод своих статей на английский – это уже дело самих авторов, если они в этом заинтересованы. Исключение предполагается делать только для одной-двух статей в год, признанных редакцией достойными поощрения в виде публикации на английском силами редакции (но это означает задержку английского текста минимум на год). Результаты такого эксперимента можно найти в последнем номере юбилейного тома журнала.

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ОЦЕНКА ДЕЙСТВИЯ ПРОТИВОГОЛОЛЕДНЫХ РЕАГЕНТОВ РАЗНОГО ХИМИЧЕСКОГО СОСТАВА НА РОСТ ТРАВЯНИСТЫХ РАСТЕНИЙ И ПОЧВЕННОЕ ДЫХАНИЕ

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Представлены результаты сравнительного изучения воздействия применяемых в Санкт-Петербурге противогололедных средств (ПГС) различного состава на рост травянистых растений и почвенное дыхание, проведенного с целью определить наименее опасные и установить допустимые концентрации их применения. Были исследованы ПГС на основе хлоридов натрия, магния, кальция, ацетата калия и формиата натрия, которые в условиях лабораторного и полевого экспериментов вносились в дерново-подзолистую почву в концентрациях 20, 50 и 150 г/м^2. Показателями воздействия ПГС на растения служили биомасса газонных трав и длина корней проростков пшеницы. В лабораторных опытах средние и высокие дозы хлоридов значительно подавляли почвенное дыхание и также снижали длину проростков семян пшеницы и биомассу газонных трав. В отдельных случаях угнетение растений наблюдалось уже при минимальном уровне хлоридных реагентов, а при высоком уровне оно достигало 100%. Среди хлоридных ПГС наименее токсичным оказался хлорид магния. Ацетатные и формиатные реагенты не оказывали на растения и почвенные микроорганизмы столь же выраженное токсическое действие. В некоторых случаях отмечался их стимулирующий эффект, в частности, на почвенное дыхание. В полевых экспериментах в течение вегетационного сезона ингибирующее действие хлоридных ПГС постепенно нивелировалось природными факторами (атмосферные осадки и др.) до слаботоксичного или нейтрального. Ацетатные и формиатные ПГС при сравнении с хлоридными менее опасны для растений и, судя по почвенному дыханию, для микроорганизмов и могут рекомендоваться к использованию в городской среде. В условиях промывного водного режима Санкт-Петербурга рекомендуется, чтобы концентрации применяемых противогололедных средств не превышали 50 г/м^2.

Ключевые слова: *противогололедные средства, почвы, растения, микроорганизмы, токсичность.*

EVALUATION OF THE IMPACTS OF ICE CONTROL MATERIALS HAVING DIFFERENT CHEMICAL COMPOSITIONS ON GRASS GROWTH AND SOIL RESPIRATION

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Comparative evaluation of the impact of ice control materials (ICM) used in Saint Petersburg grass growth and soil respiration was carried out to select the least hazardous of ICM and to establish their tolerable dosages. The ICM studied were based on sodium, magnesium or calcium chlorides, or potassium acetate, or sodium formate. ICM solutions were applied to sod-podzolic soils to make a 20, 50 or 150 g/m^2 application dose. Grass conditions were assessed by lawn grass biomass and wheat sprout root length. Under laboratory conditions, medium and high dosages of chlorides suppressed all parameters, the least toxic being magnesium chloride. Acetates and formates were less toxic and in some cases even stimulatory, in particular, for soil respiration. Under field conditions, the impact of chlorides gradually declined over the vegetative season, most likely because washing out by atmospheric precipitates, which are usual for the rainy climate of Saint Petersburg. On a whole, acetates and formates are the least hazardous among ICM tested. Under Saint-Petersburg climatic conditions, application dosages of ICM should not exceed 50 g/m^2.

Keywords: *ice control materials, soil, grass, toxicity.*

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Введение

В последние годы в России появилось значительное число новых противогололедных средств (ПГС). Во многом подобное изобилие обусловливается маркетинговыми решениями. Вследствие актуальности и масштабов проблемы под разными торговыми марками могут скрываться одни и те же препараты, внедрение которых связано с потенциальными доходами производителей. Сейчас на рынке фигурирует несколько десятков ПГС различного химического состава. Некоторые из них широко и бесконтрольно используются на магистралях городов на постоянной основе.

В связи с этим важной природоохранной задачей является оценка последствий применения различных ПГС на улицах российских городов. Это обусловливается тем, что в мегаполисах ПГС являются одним из главных антропогенных факторов, негативно влияющих на окружающую среду, в первую очередь – на высшие растения и почвенные микроорганизмы.

Известно, что одним из наиболее важных показателей качества почв служит жизненное состояние и биомасса произрастающих на них растений. ПГС прежде всего повреждают растительность опосредованно, через загрязненную почву [10]. Поступая вместе с тающим снегом в придорожные почвы и накапливаясь в них, ПГС изменяют их химический состав и нарушают физические характеристики. Это приводит к структурным и функциональным изменениям почвенной экосистемы, что чревато гибелью растений [8]. В то же время непосредственно на растения ПГС могут попадать через воздух в форме брызг, пыли и аэрозолей, что вызывает отмирание стеблей и почек молодых побегов, задержку возобновления роста весной, снижение фотосинтетического потенциала. Степень воздействия ПГС на почвы и растительность зависит от множества факторов. В их числе – расстояние от проезжей части, продолжительность воздействия, гранулометрический состав почвы, наличие или отсутствие дренажа, количество осадков и другие [9].

Выделение углекислого газа почвой в первую очередь определяется дыханием содержащихся в ней микроорганизмов в процессе окисления и минерализации органического вещества ими. Изменение состояния микробоценозов, вызванное загрязнением почв ПГС, может привести к нарушению экологического равновесия и постепенной деградации экосистемы, что негативно скажется на почвенном плодородии. Микроорганизмы являются чувствительными биоиндикаторами, быстро реагирующими на изменения в среде. В связи с этим микробиологические показатели с успехом используются для экологической оценки состояния почв в условиях антропогенной нагрузки [2]. Однако, несмотря на первостепенную роль микроорганизмов в функционировании биосферы, сведения о микробиологическом состоянии почв, загрязненных ПГС, малочисленны, а данные о влиянии доз различных ПГС на интенсивность процессов, контролируемых микроорганизмами, практически отсутствуют.

В последние годы вопросам негативного воздействия ПГС на окружающую среду уделяется все большее внимание. Однако, как правило, публикации на эту тему освещают действие одного-двух реагентов (в основном из хлоридной группы).

В Санкт-Петербурге среди различных ПГС наиболее часто для борьбы с обледенением используют реагенты на основе хлоридов натрия, кальция или магния. В последнее время все большее распространение получают также реагенты ацетатной и формиатной групп.

Целью настоящей работы было исследовать характер и степень воздействия ПГС различного химического состава, применяемых в Санкт-Петербурге, на растения и почвенное дыхание и определить наиболее безопасные ПГС и допустимые дозы их внесения.

Объекты и методы

Эксперименты по загрязнению окультуренной дерново-подзолистой суглинистой почвы противогололедными реагентами проводились в лабораторных и полевых условиях. Для этого были выбраны ПГС, представляющие каждую из трех основных химических групп: техническая соль (хлорид натрия), «ТОР» (хлорид кальция), «Бишофит» (хлорид магния), «Нордвэй» (ацетат калия) и «Clearway» (формиат калия). В полевых опытах вместо реагента «ТОР» использовался реагент «Ежик» (смесь хлоридов кальция и натрия). Производителем ПГС «ТОР» и «Ежик» являлось ООО «Зиракс», «Нордвэя» – ООО «Профлинг», «Бишофита» – ЗАО «Бишофит-Авангард», а «Clearway» – концерн «Kemira».

ПГС в полевом и лабораторном экспериментах вносили в исследуемую почву в дозах 20, 50 и 150 г/м^2, соответствующих нормативам ТУ. Полученные результаты сравнивали с показателями незагрязненных контрольных образцов.

Натурный мелкоделяночный эксперимент был заложен в 4-кратной повторности на территории опытного поля Аграрного университета (г. Пушкин) с целью выявить степень уменьшения токсичности загрязненных ПГС почв в течение вегетационного сезона вследствие процессов самоочищения.

После загрязнения ПГС опытных делянок в начале вегетационного сезона (в мае) высевали газонные травы (травосмесь «Универсал»). Осенью (в сентябре) производили полный укос трав с делянок для определения их биомассы, служащей интегральным показателем при оценке физиологического состояния растений. Тогда же отбирали образцы контрольных и загрязненных почв для проведения лабораторных исследований (фитотестирование и микробиологические опыты).

Лабораторный опыт проводили с целью выявить воздействие неизмененных концентраций ПГС (в отсутствие внешних природных факторов) на состояние растений и почвенное дыхание.

Для проведения лабораторного эксперимента почву, увлажненную до 60% полной влагоемкости, помещали в вегетационные сосуды объемом 1 л. Реагенты вносили в почву в растворенном виде. После загрязнения указанными дозами ПГС засевали почвы газонными травами (травосмесь «Универсал»). Через три-четыре недели по достижении определенной высоты надземную часть растений срезали, затем путем взвешивания определяли ее биомассу.

Показателем степени воздействия ПГС на растения как в натурных, так и в лабораторных условиях, кроме биомассы газонных трав, служили различия в длине корней проростков пшеницы (*Triticum aestivum L.*), выросших на загрязненных почвах, по сравнению с контрольной пробой[1].

Интенсивность выделения CO_2 (иначе – почвенное дыхание), которая характеризует интегральную напряженность протекающих в почвах процессов биодеструкции органического вещества, использовали в качестве показателя микробиологического состояния почв. В настоящее время почвенное дыхание считается одним из наиболее важных индикаторов состояния не только микробного комплекса почв, но и почвенной экосистемы в целом [4, 5]. Почвенное дыхание определяли в лабораторных условиях адсорбционным методом [1].

Достоверность различий между полученными результатами оценивали по критерию Манна-Уитни и дополнительно по критерию Стьюдента. Последний использовали на основании того, что в полевых опытах случайные ошибки неизбежны и даже при малом числе параллельных наблюдений они соответствуют t-распределению Стьюдента [3].

Результаты и обсуждение

Результаты определения длины корней проростков пшеницы, выращиваемых в лабораторных условиях, при действии различных ПГС представлены в таблице 1.

Из таблицы 1 видно, что при максимальной концентрации хлоридных реагентов подавление проростков пшеницы достигало 90–100%. Серьезное угнетение – от 32 до 52% – наблюдалось даже при минимальных дозах ПГС. В то же время у ацетатного и формиатного

Табл. 1

Воздействие ПГС на длину корней проростков пшеницы в лабораторном опыте

Реагент	Доза ПГС, г/м^2	Длина корня, мм*	Δ, %**
Контроль	0	16,0 ± 2,2	
Техническая соль	20	8,4 ± 1,4	–47,7 ^#
	50	5,3 ± 0,3	–66,9 ^#
	150	0	–100 ^#
Бишофит	20	10,8 ± 2,1	–32,3 #
	50	9,7 ± 0,6	–39,6 #
	150	1,6 ± 0,1	–90,0 ^#
TOR	20	7,6 ± 0,3	–52,8 ^#
	50	4,7 ± 0,1	–71,0 ^#
	150	0,7 ± 0,2	–96,0 ^#
Нордвэй	20	23,2 ± 1,6	+45,2 ^#
	50	18,4 ± 1,4	+14,8
	150	7,3 ± 0,2	–54,6 ^#
Clearway	20	19,2 ± 4,3	+20,2
	50	18,4 ± 2,2	+14,8
	150	12,6 ± 0,4	–21,3 ^

* Среднее значение 4 параллельных измерений ± стандартное отклонение.

** Δ – отличие от контроля (%); ^ – $p \leq 0,05$ (по критерию Манна-Уитни).

– $p \leq 0,05$ (по критерию Стьюдента); отсутствие значков ^ и/или # означает недостоверность различия по одному либо обоим критериям.

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[1] Методика выполнения измерений всхожести семян и длины корней проростков высших растений для определения токсичности техногенно загрязненных почв. М-П-2006. Федеральный реестр (ФР). ФР.1.39.2006.02264. Санкт-Петербург; 2009.

реагентов «Нордвэй» и «Clearway» угнетение началось только при максимальных концентрациях ПГС – 54 и 21% соответственно. При низких же и средних дозах, наоборот, в некоторых вариантах отмечалась стимуляция роста корней (до 45%).

Схожие закономерности были выявлены в опыте по учету биомассы (табл. 2). Ацетатный и формиатный реагенты в малых и средних концентрациях не ингибировали рост трав, а достигаемое угнетение от их воздействия оказалось менее значительным (максимум – 34% у реагента «Clearway»). Влияние минимальных доз хлоридов оказалось опасно токсичным для газонных трав: угнетения на 58% и более, и уже при средних дозах семена практически не взошли (отмечались лишь единичные всходы, чья масса не достигала 1% контроля).

Необходимо подчеркнуть, что, по сравнению с пшеницей, восприимчивость газонных трав к действию хлоридов может считаться более репрезентативной, поскольку именно травы используют в уличных посадках.

Судя по изменениям почвенного дыхания, почвенные микроорганизмы также испытывали угнетение от действия противогололедных реагентов, однако в меньшей степени, чем растения (табл. 3). Минимальные дозы всех исследованных реагентов не оказывали достоверного воздействия на почвенное дыхание. Наиболее токсичной оказалась техническая соль, которая существенно ингибировала дыхательную активность при средних и максимальных дозах (–40 и –53% соответственно по сравнению с контролем). Хлоридные реагенты «ТОР» и «Бишофит» снижали (в среднем на треть) интенсивность почвенного дыхания при их внесении в максимальных количествах. Известно, что критический порог устойчивости почвенных систем составляет потерю не более 30% биоорганического потенциала от фонового или контрольного уровня [13]. Таким образом, полученные результаты свидетельствуют о деградации микробоценозов исследованных почв, что в свою очередь указывает на низкую устойчивость изученных почвенных систем в целом к токсическому воздействию высоких доз хлоридных ПГС.

Ацетатные и формиатные реагенты стимулировали почвенное дыхание. В то же время выраженное превышение интенсивности дыхания над контрольными показателями (до 73,9% у «Нордвэя») нельзя считать положительным явлением, поскольку подобная гипертрофированная активность способна вывести систему из режима нормального функционирования и в дальнейшем привести к ее разрушению [6, 7].

Табл. 2

Воздействие ПГС на биомассу газонных трав в лабораторном опыте

Реагент	Доза ПГС, г/м²	Биомасса, г*	∆, %**
Контроль	0	2,48 ± 0,1	
Техническая соль	20	0,18 ± 0,0	–92,9 ^#
	50	0,01 ± 0,0	–99,8 ^#
	150	0	–100 ^#
Бишофит	20	1,03 ± 0,0	–58,3 ^#
	50	0,004 ± 0,0	–99,8 ^#
	150	0	–100 ^#
TOR	20	0,12 ± 0,0	–95,0 ^#
	50	0	–100 ^#
	150	0	–100 ^#
Нордвэй	20	2,1 ± 0,1	–15,2 ^
	50	2,53 ± 0,1	+2,0
	150	2,1 ± 0,1	–15,2 ^
Clearway	20	3,15 ± 0,1	+26,7 ^#
	50	2,58 ± 0,1	+4,0
	150	1,63 ± 0,0	–34,2 ^#

* Среднее значение по 3 параллельным измерениям ± стандартное отклонение.

** ∆ – отличие от контроля (%).

^ – $p \leq 0{,}05$ (по критерию Манна-Уитни); # – $p \leq 0{,}05$ (по критерию Стьюдента); отсутствие значков ^ и/или # означает недостоверность различия по одному либо обоим критериям.

В целом результаты экспериментов по загрязнению почвы ПГС в лабораторных условиях продемонстрировали опасную токсичность хлоридных реагентов для растений и микроорганизмов и менее токсичное действие ацетатных и формиатных реагентов. Из числа хлоридных ПГС наиболее токсичной оказалась техническая соль.

Стимуляцию формиатным и ацетатным реагентами почвенного дыхания и роста растений можно объяснить действием калия, входящего в состав этих препаратов. В то же время хлоридные ПГС снижали эти показатели, что согласуется с исследованиями зарубежных ученых. Уинтерс с коллегами установил, что ацетаты в составе ПГС менее вредны для растений, нежели хлориды натрия [12]. Хорнер также пришел к выводу, что ацетаты в концентрациях, используемых в ПГС, не наносят вреда наземной растительности, за исключением тех случаев, когда их высокие уровни вызывают осмотический стресс в корневой зоне [11]. Но и в этом случае опасность ацетатов неоднозначна, поскольку он является питательным веществом для многих видов микроорганизмов, а сами реагенты обычно разлагаются в течение 2–4 недель [10].

Поскольку зимой противогололедные реагенты остаются в почве и со временем накапливаются в ней, то даже минимальные вносимые дозы некоторых реагентов могут стать опасными для жизнедеятельности растений и почвенных микроорганизмов. Однако по окончании периода обработок улиц ПГС, в течение вегетационного сезона, реагенты в почве подвергаются действию различных внешних факторов. В частности, климатические условия Северо-Западного региона РФ характеризуются большим количеством осадков. С целью выявления динамики токсичности загрязненной ПГС почвы для растений и микроорганизмов в течение вегетационного сезона были заложены полевые опыты.

Результаты фитотестирования проб загрязненных ПГС полевых почв, отобранных по истечении вегетационного сезона, представлены в таблице 4.

Как видно, к осени действие хлоридных ПГС на проростки пшеницы в полевом эксперименте стало, в основном, менее токсичным, чем в лабораторном эксперименте, а с «Бишофитом» длина корней даже превзошла контрольные показатели.

Степень угнетения растительной биомассы хлоридными ПГС также заметно уменьшилась. Действие хлоридов магния и кальция на биомассу соответствовало «практически не токсичному», как видно в таблице 5.

Табл. 3

Дыхание почвы (лабораторный опыт)

Реагент	Доза ПГС, г/м²	мг CO$_2$/100 г сухой почвы в сутки*	∆, %**
Контроль	0	28,0 ± 0,3	–
Техническая соль	20	28,1 ± 1,0	+0,7
	50	16,6 ± 0,3	–40,7 ^#
	150	13,1 ± 1,1	–53,2 #
Бишофит	20	25,4 ± 1,1	–9,5
	50	27,1 ± 1,2	–3,4
	150	20,5 ± 1,1	–26,4
TOR	20	42,2 ± 1,2	+50,6 #
	50	25,4 ± 0,9	–9,5
	150	18,2 ± 1,0	–35,2 #
Нордвэй	20	45,6 ± 4,4	+62,9 ^#
	50	32,9 ± 2,1	+17,5
	150	48,7 ± 3,6	+73,9 ^#
Clearway	20	44,1 ± 0,6	+57,3 ^#
	50	30,8 ± 1,3	+9,9
	150	35,7 ± 1,6	+27,4 ^#

* Среднее по 3 определениям ± стандартное отклонение.

** ∆ – отличие от контроля.

^ – $p \le 0{,}05$ (по критерию Манна-Уитни); # – $p \le 0{,}05$ (по критерию Стьюдента); отсутствие значков ^ и/или # означает недостоверность различия по одному либо обоим критериям.

Табл. 4

Воздействие ПГС на длину корней проростков высших растений в полевом опыте

Реагент	Доза ПГС, г/м^2	Длина корня, мм*	∆, %**
Контроль	0	35,0 ± 0,2	–
Техническая соль	20	23,0 ± 0,3	–34,3 $^{\wedge\#}$
	50	23,5 ± 0,7	–33,0 $^{\wedge\#}$
	150	17,6 ± 0,2	–49,8 $^{\wedge\#}$
Бишофит	20	39,4 ± 2,6	+12,6
	50	32,2 ± 1,6	–8,1
	150	45,8 ± 2,1	+30,8 $^{\wedge\#}$
«Ежик»	20	33,2 ± 3,9	–5,1
	50	28,8 ± 1,6	–17,7 $^{\#}$
	150	22,1 ± 1,6	–36,9 $^{\wedge\#}$
Нордвэй	20	26,2 ± 0,4	–25,1 $^{\wedge\#}$
	50	31,1 ± 0,5	–11,2 $^{\wedge\#}$
	150	18,5 ± 2,2	–47,2 $^{\wedge\#}$
Clearway	20	23,0 ± 2,9	–32,8 $^{\wedge\#}$
	50	25,7 ± 1,7	–24,9 $^{\wedge\#}$
	150	16,8 ± 1,2	–50,9 $^{\wedge\#}$

* Среднее по 4 параллельным измерениям ± стандартное отклонение;

** ∆ – отличие от контроля (%); ^ – $p \leq 0{,}05$ (по критерию Манна-Уитни); # – $p \leq 0{,}05$ (по критерию Стьюдента); отсутствие значков ^ и/или # означает недостоверность различия по одному либо обоим критериям.

Табл. 5

Воздействие ПГС на биомассу газонных трав в полевом опыте

Реагент	Доза ПГС, г/м^2	Биомасса, г*	∆, %**
Контроль	0	347,5 ± 7,8	
Техническая соль	20	278,0 ± 4,9	–20,0
	50	133,9 ± 4,0	–61,5 $^{\wedge}$
	150	49,8 ± 2,2	–85,7 $^{\wedge\#}$
Бишофит	20	358,8 ± 25,4	+3,3 $^{\#}$
	50	343,8 ± 23,3	–1,1 $^{\#}$
	150	272,5 ± 25,3	–21,6 $^{\#}$
Ежик	20	362,5 ± 51,8	+4,3 $^{\#}$
	50	333,8 ± 16,4	–3,9 $^{\#}$
	150	250 ± 28,1	–28,1 $^{\#}$
Нордвэй	20	216,2 ± 5,4	–37,8
	50	251,4 ± 7,8	–27,7
	150	66,9 ± 2,4	–80,7 $^{\wedge\#}$
Clearway	20	261,8 ± 16,4	–24,7 $^{\#}$
	50	303,0 ± 9,2	–12,9 $^{\#}$
	150	264,6 ± 29,1	–23,9 $^{\#}$

* Среднее значение по 3 параллельным измерениям ± стандартное отклонение;

** ∆ – отличие от контроля (%); ^ – $p \leq 0{,}05$ (по критерию Манна-Уитни); # – $p \leq 0{,}05$ (по критерию Стьюдента); отсутствие значков ^ и/или # означает недостоверность различия по одному либо обоим критериям.

Некритичное для микробоценозов снижение уровня почвенного дыхания отмечалось лишь в варианте со средними концентрациями формиата, а в отдельных случаях (средняя концентрация хлорида магния и максимальная – ацетата) выявлена незначительная стимуляция микробиологической активности.

Результаты полевых экспериментов демонстрируют значительное снижение токсичности загрязненной ПГС почвы в течение лета и осени. Его можно объяснить, главным образом, вымыванием солей хлоридных ПГС из верхних горизонтов почвы выпадающими осадками. У ацетатных и формиатных реагентов за этот же период отмечено нивелирование стимулирующего действия, что, по всей видимости, обусловлено теми же факторами.

Техническая соль и в этом случае сильнее прочих хлоридов подавляла газонные травы, но при слабой и средней концентрациях ее влияние уже не превышало степени умеренной токсичности.

В то же время подавление надземной биомассы формиатами осталось на прежнем уровне, а в случае ацетатов даже немного усилилось.

Что касается активности микроорганизмов, то по окончании вегетационного сезона действие всех противогололедных реагентов становится нейтральным – они не оказывали существенного влияния на интенсивность почвенного дыхания (табл. 6).

Исследования показали, что степень токсичности в большинстве загрязненных ПГС проб к концу вегетационного периода снижалась (за единичными исключениями). В этой связи есть основания считать, что использование имеющихся ПГС при промывном водном режиме Санкт-Петербурга (и всего Северо-Западного региона) не является для растений чрезвычайно опасным, как это видится по данным лабораторных экспериментов, где концентрации загрязнителя неизменны. Тем не менее, необходимо учитывать изменчивость внешних факторов, например, вероятность засушливого лета. Кроме того, известно, что максимальное токсическое действие реагентов проявляется сразу по окончании сезона противогололедных обработок, когда растения вступают в период активного роста и наименее устойчивы. Соответственно, вред от ПГС в данное время максимален.

Тенденции рынка противогололедных средств таковы, что хлоридные реагенты занимают сегодня доминирующее положение, поскольку они заметно дешевле ацетатных и формиатных реагентов. В частности, в

Табл. 6

Дыхание загрязненной ПГС почвы, мг CO_2/100 г сухой почвы, в сутки (полевой опыт)

Реагент	Доза, г/м^2	мг CO_2/100 г сухой почвы в сутки*	∆, %**
Контроль	0	9,7 ± 0,9	
Техническая соль	20	9,9 ± 0,9	+2,1
	50	10,6 ± 0,7	+9,3
	150	8,7 ± 0,8	–10,3
Бишофит	20	10,7 ± 1,5	+10,0
	50	13,1 ± 1,8	+35,0
	150	9,9 ± 1,4	+2,9
Ежик	20	9,9 ± 1,4	+2,8
	50	9,3 ± 0,5	–4,3
	150	10,5 ± 1,4	+7,8
Нордвэй	20	9,8 ± 0,9	+1,0
	50	10,1 ± 1,0	+4,0
	150	12,4 ± 0,4	+27,8 $^{\#}$
Clearway	20	8,5 ± 0,5	–12,4
	50	7,6 ± 0,1	–21,6 $^{\#}$
	150	8,5 ± 1,2	–12,4

* среднее по 4 параллельным измерениям CO_2 ± стандартная ошибка;

** Δ – отличие от контроля;

^ – $p \leq 0,05$ (по критерию Манна-Уитни); # – $p \leq 0,05$ (по критерию Стьюдента); отсутствие значков ^ и/или # означает недостоверность различия по одному либо обоим критериям.

Санкт-Петербурге в ближайшем будущем не планируется отказываться от применения технической соли на магистралях города (по утверждениям работников соответствующих служб). Однако при выборе из хлоридных реагентов предпочтительно использовать хлориды магния (реагент «Бишофит» и схожие с ним по химическому составу ПГС). Для еще большего снижения опасности для окружающей среды целесообразно применение реагентов «Нордвэй» и «Clearway».

При расчете концентраций применяемых ПГС следует ориентироваться на результаты лабораторных экспериментов, согласно которым рекомендуется не превышать дозы 50 г/м^2.

Выводы

– Ацетатные и формиатные реагенты («Нордвэй» и «Clearway») представляют меньшую экологическую опасность для жизнедеятельности высших растений и почвенных микроорганизмов по сравнению с хлоридными реагентами.

– Среди хлоридных ПГС, применяющихся в Санкт-Петербурге, хлориды магния («Бишофит») оказались менее токсичными в сравнении с хлоридами кальция и натрия.

– В течение вегетационного сезона токсичность хлоридных ПГС в почве снижается вследствие вымывания их солей из верхних почвенных горизонтов осадками. Тем не менее, рекомендуется не допускать превышения концентрации ПГС 50 г/м^2, которую можно считать приемлемой для использования на улицах городов.

– Во избежание накопления отдельных химических элементов в почве целесообразно довести число применяемых ПГС до четырех-пяти, чтобы иметь возможность чередовать их применение.

– Дальнейшие разработки в области ПГС должны быть направлены на реагенты комбинированного состава, которые позволяли бы эффективно плавить снег и лед и не наносить при этом значительного ущерба окружающей среде.

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СВЯЗАННЫЕ С УРБАНИЗАЦИЕЙ ФАКТОРЫ ЗАБОЛЕВАЕМОСТИ САХАРНЫМ ДИАБЕТОМ ПЕРВОГО ТИПА

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Большая часть населения сейчас живет в городских условиях. Профиль загрязнений городской среды изменяется под влиянием автомобильного дорожного комплекса (АДК). Его важнейшим загрязняющим продуктом служат твердые пылевые частицы, в состав которых входят алюмосиликаты. Многие соединения алюминия известны как адъюванты, усиливающие иммунный ответ, в том числе на аутоантигены. Сахарный диабет 1-го типа (СД1) — аутоиммунное заболевание. Цель работы — изучить с использованием данных геоинформационных систем (ГИС) особенности медицинской географии СД1 в России и выявить связанные с урбанизацией факторы повышения заболеваемости. Такой подход для исследования распространенности аутоиммунных болезней ранее не применялся. Исследована заболеваемость СД1 в 83 регионах Российской Федерации в 2008—2017 гг. Отмечены более чем 20-кратные различия между регионами РФ по заболеваемости СД1. Самая высокая она в Псковской области (77,31 на 100 тыс. населения), самая низкая — в Республике Дагестан (3,56 на 100 тыс. населения). Установлены достоверные корреляции между заболеваемостью СД1, географической плотностью сети автомобильных дорог с твердым покрытием, ежегодным выбросом загрязняющих атмосферу веществ из стационарных источников и количеством автобусов на 100 тыс. населения. Эффекты первых двух факторов мультипликативные, эффект третьего аддитивен к ним.

***Ключевые слова**: автомобильно-дорожный комплекс, геоэпидемиология, аутоиммунные заболевания, сахарный диабет I типа, урбанизация, твердые пылевые частицы.*

URBANIZATION-RELATED FACTORS OF THE INCIDENCE OF TYPE I DIABETES MELLITUS

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Most people are living now under urbanized conditions. Air pollutants composition depends on highway network (HN). An important component of HN-derived pollutants is solid dust particles (SDP), which contain aluminum silicates. Among aluminum-containing compounds, many are known as adjuvants, which enhance immune responses, including those to autoantigens. Type 1 diabetes mellitus (DM1) is an autoimmune condition. The objective of the present work is to use geoinformation system (GIS) data for examining the medical geography of DM1 incidence in Russia as it relates to factors associated with urbanization. Such approaches were not employed earlier. SD1 incidence rates in 83 regions of Russia in 2008-2017 show that differences in the rates may be as high as more than 20-fold. The highest rate is in Pskov Oblast (77.31 per 100 000 people), whereas the lowest rate in Dagestan (3.36 per 100 000 people). Significant correlations were found between SD1 incidence on one hand and HN density, air pollutant discharges from stationary sources, and the number of buses per 100 000 population on the other. The effects of the first two factors are multiplicative, and the effect of the third one is additive to them.

***Keywords**: highway network, geographic epidemiology, autoimmune conditions, Type 1 diabetes mellitus, urbanization, solid dust particles.*

Введение

По мере усиления урбанизации и увеличения продолжительности жизни растет доля аутоиммунной патологии в структуре заболеваемости населения [17, 48]. Несмотря на успехи в понимании патогенеза ряда аутоиммунных заболеваний [17, 47], причины многих из них остаются предметом дискуссий [14, 15, 43, 44, 46, 48].

В России как одной из самых больших и разнообразных по природным и антропогенным условиям стран мира вопросы медицинской географии и ее связи с заболеваемостью традиционно привлекали внимание ученых, что обусловило формирование сильной геоэпидемиологической школы, одной из старейших в мире [11, 18].

Геоэпидемиологический подход позволил выявить причины развития и распространения таких инфекционных заболеваний, как бруцеллез, грипп, клещевой энцефалит [1, 6, 10]. Геоинформационные системы (ГИС) успешно применялись для изучения закономерностей пространственно-временного распределения природных очагов сибирской язвы и для предупредительного эпидемиологического надзора за чумой, брюшным тифом, холерой, геморрагической лихорадкой с почечным синдромом, а также для паспортизации очагов туляремии и болезни Лайма [1, 6, 10, 31]. Еще один пример биомедицинского применения ГИС-технологии – изучение системы обращения с медицинскими отходами и разработка дифференциальных схем их утилизации для каждого региона РФ [13].

Использование ГИС-технологий позволяет:

– анализировать (с учетом ранжирования и динамики) неинфекционную заболеваемость населения и медико-демографические показатели различных регионов;

– анализировать качество среды обитания: атмосферного воздуха, почвы населенных мест, воды в системах централизованного водоснабжения (с учетом ранжирования, динамики и расположения источников загрязнения);

– обосновывать меры санитарной охраны территорий с учетом распространенности природно-очаговых инфекций и географии их очагов;

– анализировать инфекционную и паразитарную заболеваемость населения (с учетом ранжирования и динамики) [11].

В новой медицинской области – аутоиммунологии [17] – ГИС до настоящего времени не применялись. Одна из причин – отставание существующих редукционистских классификаций болезней от развития современной биомедицины. Болезни классифицируются и учитываются официальной эпидемиологической статистикой в основном, как и полвека назад, по органам и системам. В то же время, около 90 заболеваний, аутоиммунный патогенез которых доказан, диспергированы по самым разным группам нозологических единиц – от кожных до психических. Тогда как полвека назад представления об аутоиммунной патологии сводились лишь к недугам, находящимся в сфере компетенции ревматологов, теперь стала ясна единая аутоиммунная природа многих болезней, не подлежащих ревматологическому учету. Использование медико-географической статистики для анализа заболеваемости аутоиммунными болезнями в больших популяциях представляется весьма перспективным.

Россия (РФ) – самая обширная страна мира (17125191 км²), где представлены самые разные природно-географические зоны – от арктической до субтропической, при населении на конец 2017 г. 146880432 человека [2]. Социально-экономическое развитие и степень урбанизации разных регионов РФ весьма неоднородны, доля городского населения в них составляет 74% и постоянно растет [2].

Доказано, что загрязнение воздуха оказывает влияние не только на органы дыхания, но также на большинство других органов и систем организма [21, 33, 37, 42]. По оценкам ВОЗ, около 500 тыс. случаев смерти от рака легких и 1,6 миллиона случаев смерти от хронической обструктивной болезни легких могут быть связаны с загрязнением атмосферного воздуха. Кроме этого, загрязнение воздуха провоцирует 19% случаев смерти от всех сердечно-сосудистых заболеваний и 21% смертельных инсультов [21, 42].

Поглощаемые фагоцитами дыхательных путей пылевые микро- и наночастицы способны вызывать стойкие изменения в иммунной системе, способствующие развитию аллергического ринита [26]. После воздействия твердых пылевых частиц (ТПЧ) в иммунной системе могут происходить разнонаправленные изменения, затрагивающие механизмы и эффективность иммунологической толерантности [21, 24].

Предметом анализа в настоящей работе была заболеваемость сахарным диабетом 1-го типа (СД1), практически для всех случаев которого доказан аутоиммунный патогенез [17], связанный с действием как природных (например, вирусы), так и антропогенных (нитрозамины, пептиды альбумина коровьего молока, некоторые лекарства) факторов [16, 31]. Заболеваемость СД1 в РФ растет, особенно среди детей [18, 35]. Цель исследования состояла в выявлении факторов городской среды, влияющих на заболеваемость СД1 в России.

Материалы и методы исследования

В качестве анализируемой была взята группа «Все население РФ» (лица, проживающие на территории РФ с рождения или в течение 10 лет и более), а в качестве изучаемого показателя – *заболеваемость с впервые установленным диагнозом СД1 на 100 тыс. насе-*

ления (далее –*incidence* как зависимая переменная в модели). Временной период изучения: с 2008 по 2017 г. включительно (при этом статистика по загрязнению была учтена с 2005 по 2015 г.).

Исследование охватывало всю территорию РФ – Центральный, Северо-Западный, Южный, Северо-Кавказский, Приволжский, Уральский, Сибирский, Дальневосточный федеральные округи – по 83 регионам, входившим в состав РФ с года начала исследования.

Заболеваемость в каждом регионе РФ рассчитывали по данным официальных сборников статистических материалов РФ[1-4].

Учитывались следующие возможные факторы заболеваемости:

- количество выбросов загрязняющих веществ в атмосферный воздух от стационарных источников в каждом регионе отдельно в тысячах тонн с 2005 по 2015 г. (далее – *air* как параметр модели или выбросы загрязняющих веществ в атмосферный воздух как показатель);
- количество загрязненных сточных вод в каждом регионе РФ в отдельности в миллионах м^3 с 2005 по 2015 г. (далее – *water* как параметр модели или загрязненные сточные воды как показатель);
- географическая плотность сети дорог общего пользования с твердым покрытием, в расчете на 1000 км^2 по общей протяженности дорог на конец 2005–2015 г. (далее – *road* как параметр модели или плотность сети дорог общего пользования с твердым покрытием как показатель);
- количество автобусов общего пользования на 100 тыс. населения (далее – *bus* как параметр модели или количество автобусов общего пользования как показатель).

Предварительно в каждом регионе методом скользящего среднего (rolling mean) [53] подсчитывали впервые выявленные случаи СД1 на 100 тыс. населения в изучаемый период.

Описательная статистика включала в себя расчеты среднего арифметического и стандартного отклонения (Mean ± SD), медианы и 1-го и 3-го квартилей (Median, [Q1;Q3]) и указания на минимальное и максимальное значения (min-max).

Для выявления влияния изучаемых факторов на заболеваемость СД1 использовался регрессионный анализ. Выбор регрессионной модели был обусловлен тем, что заболеваемость является дискретной неотрицательной величиной. Широко используемая модель Пуассона в данном случае не применялась, поскольку оснований считать, что среднее и дисперсия между собой равны, не было. Поэтому была выбрана отрицательная биномиальная модель (negative binomial), с помощью которой можно учитывать избыточную дисперсию данных (overdispersion), что позволяет получать несмещенные оценки [39, 52].

На первом этапе статистического анализа выбранные факторы включались в **модель, где учтены все возможные взаимодействия между ними (модель 1)**, поскольку предполагалось, что совокупное влияние факторов более значимо, чем влияние каждого фактора в отдельности. Так как кривые распределения величин изучаемых факторов заметно смещены к нулю, эти величины были предварительно прологарифмированы. Оценки разных моделей производили в среде R version 3.5.2 [45] при помощи функции glm.nb(MASS) [51]. Синтаксис функции был следующим:

fit <- glm.nb(incidence~log(bus)*log(road)*log(air)*log(water)+offset(log(1000))).

Далее производился поиск оптимальных моделей при помощи процедуры обратной пошаговой регрессии (stepAIC) и при помощи ручного обновления модели (update.formula(fit)). Для описания отобранных моделей использовались: параметр распределения θ, логарифм максимального правдоподобия (Log-Likelihood, LR), отклонение (deviance), степень свободы (d.f.). Выбор наилучшей модели для объяснения данных основывался на наименьшем значении информационного критерия Акаике (AIC). На основе коэффициентов регрессии лучшей модели рассчитывался **коэффициент заболеваемости** (incidence rate ratio, IRR – см. ниже) и его 95% доверительный интервал (CI). Результат считали статистически значимым при вероятности ошибки первого рода (p) менее 0,005 [22].

Результаты

Выявлены существенные различия по заболеваемости СД1 между разными регионами РФ (рис. 1). Так, максимум заболеваемости был зарегистрирован в Псковской области (77,31 на 100 тыс. населения), значительно ниже заболеваемость в Западной Сибири и на юге страны, а минимален этот показатель в Республике Дагестан (3,56 на 100 тыс. населения) – различия до более чем 20-кратных! На рис. 2 показан некоторый рост заболеваемости СД1 на территории РФ с 2008 по 2017 г.

Данные по заболеваемости СД1 и выбранным урбанистическим факторам представлены в табл. 1.

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[4] Центральный научно-исследовательский институт организации и информатизации здравоохранения. Статистический материал. Москва: 2008-2016.

Рис. 1. Различия по заболеваемости СД1 в разных регионах РФ

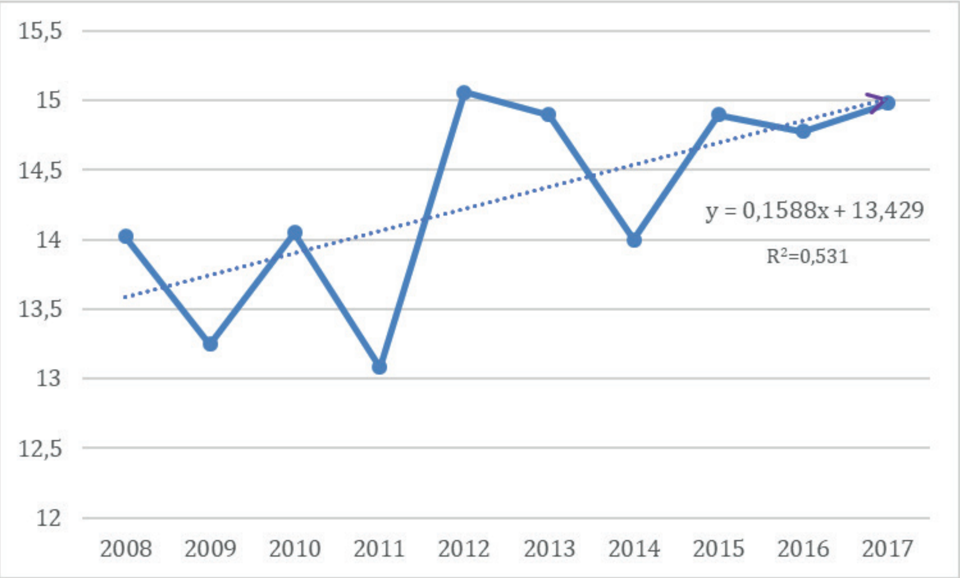

Рис. 2. Рост числа впервые выявленных случаев СД1 на 100000 человек в группе «Все население» на территории РФ с 2008 по 2017 г.

В табл. 2 представлены коэффициенты регрессионных уравнений для моделей 1–6. Установлено, что модель 1, включающая в себя сочетание всех выбранных урбанистических факторов, не содержит статистически значимых коэффициентов, связывающих их сочетанное влияние с заболеваемостью. Модели 2–5, полученные в ходе процедуры пошагового отбора, не содержат информации о влиянии количества загрязненных сточных вод на уровень заболеваемости СД1. Каждая из моделей 1–6 обосновывает один из 6 следующих выводов.

1. Нет связи между комбинированным общим влиянием всех урбанистических факторов и уровнем заболеваемости СД1.
2. Плотность автомобильных дорог и количество автобусов влияют на заболеваемость СД1.
3. Влияние плотности автомобильных дорог, количества автобусов и загрязненности воздуха на заболеваемость СД1 мультипликативное.
4. Влияние загрязненности воздуха и плотности автомобильных дорог, а также независимое влияние количества автобусов на заболеваемость СД1 мультипликативное.
5. Влияние количества автобусов и плотности сети автомобильных дорог на заболеваемость СД1 мультипликативное, возможно аддитивное влияние уровня загрязняющих атмосферу веществ на заболеваемость СД1.
6. Влияние загрязненности воздуха и количества автобусов на заболеваемость СД1 мультипликативное, аддитивно сочетающееся с влиянием плотности автомобильных дорог.

Табл. 1

Заболеваемость СД1 и значения возможных урбанистических факторов СД1 на территории РФ

Переменная модели	Показатель	Среднее арифметическое ± среднеквадратичное отклонение	Медиана [Q1;Q3]	Разброс
incidence	Число случаев впервые диагностированного СД1 на 100 тыс. населения	15,41 ± 9,87	13,02 [9,50;17,69]	5,52–77,31
bus	Число автобусов общего пользования	125,22 ± 56,85	110,86 [94,71;136,86]	49,00–407,00
road	Плотность сети дорог общего пользования с твердым покрытием	197,62 ± 178,57	172,71 [91,57;251,43]	17,14–1294,00
water	Загрязненные сточные воды	133,50 ± 172,00	86,91 [52,00;150,73]	0,45–1254,55
air	Выбросы загрязняющих веществ в атмосферный воздух	201,49 ± 154,09	164,00 [93,60;258,00]	26,55–742,64

Так как минимальное значение AIC согласно расчетам оказалось у *модели 4*, ее следует признать оптимальной. Данная модель связывает рост заболеваемости СД1 с одновременными увеличением обеспеченности населения автобусами (IRR = 1,62 (1,23–2,16)) и ростом степени загрязненности воздуха и географической плотности дорожной сети (IRR = 1,03 (1,01–1,05)).

Обсуждение

Следует прежде всего подчеркнуть, что получены достоверные свидетельства роста заболеваемости СД1 в РФ за изученный период (рис. 2).

Наиболее высок уровень заболеваемости СД1 в Псковской области. Это может быть связано с особенностями транспортного потока через город. Так, через Псковскую область и Псков проходят автомагистрали, связывающие Москву с Ригой, Санкт-Петербург с Одессой, Вильнюсом, Ригой, Львовом, Калининградом, а также большое число железнодорожных маршрутов из российских столиц в крупные зарубежные центры. Основными источниками поступления загрязняющих воздух веществ в Пскове являются транспорт (79% выбросов) и промышленные предприятия. Не меньший интерес представляют данные по региональному индексу производства в сфере деятельности «Добыча полезных ископаемых (кроме топливно-энергетических)». В 2006 г. этот индекс составил 113,4%, в 2007 году – 130,8%. По итогам 8 месяцев 2008 г. этот индекс в Псковской области вырос на 68,7% к соответствующему периоду 2007 г., и это был самый высокий показатель по РФ.

Наши данные свидетельствуют о мультипликативном влиянии загрязненности воздуха и географической плотности сети автомобильных дорог с твердым покрытием, а также о независимом влиянии относительного количества общественных автобусов на заболеваемость СД1.

Автомобилизация изменила спектр патологических состояний у людей. Наши прадеды, не знавшие авто, асфальта, бензина, тетраэтилсвинцовых присадок и тормозных колодок, передвигались на лошадях. Сап, ящур и мелиоидоз были тогда распространенными заболеваниями не только у коней, но и у людей, травмы прерывали карьеру многих знатных кавалеристов, а вот онкологии как отдельной медицинской дисциплины до эпохи автомобилизации не существовало, в том числе и потому, что пораженность неопластическими заболеваниями была куда меньше современной.

Развитие АДК происходит во всем мире и сопровождается усилением загрязнения атмосферного воздуха [4, 5, 7, 8]. По данным Федеральной службы государственной статистики РФ, с 1970 г. автопарк РФ увеличился в 47 раз, в Москве и Санкт-Петербурге – в 20 и 25 раз соответственно [9]. В Европе в настоящее время насчитывается от 480 до 600 автомобилей на тысячу человек. Дорожно-транспортная инфраструктура крупных городов России соответствует уровню автомобилизации 60–100 автомобилей на 1000 жителей. Критический с гигиенической точки зрения уровень оценивается в 170–180 автомобилей на 1000 жителей [5, 9, 12, 19]. Доля выбросов загрязняющих веществ в атмосферный воздух от автомобильного транспорта по сравнению с промышленными выбросами превышает 94% [4, 7, 8].

По литературным данным, АДК служит источником нескольких видов загрязняющих веществ. Эти загрязнители образуются в результате ряда физических взаимодействий, в том числе трения шин об асфальт, и в этом случае роль играют, в частности, различия шинных протекторов в зависимости от вида транспорта, тормозная система и дорожное покрытие. При

Табл. 2

Зависимость заболеваемости СД1 от урбанистических факторов

Параметр	Модель 1 (b (s.e.))	Модель 2 (b (s.e.))	Модель 3 (b (s.e.))	Модель 4 (b(s.e.))	Модель 5 (b (s.e.))	Модель 6 (b (s.e.))
air	7,21 (32,40)	0,12 (0,06)			0,14* (0,06)	
bus	1,34 (41,64)	0,50*** (0,14)		0,48*** (0,14)		
road	15,57 (37,37)	0,18** (0,06)				0,19** (0,06)
water	12,90 (40,95)					
air:road				0,03*** (0,01)		
air:water	–3,18 (7,00)					
bus:air	–1,23 (7,09)					0,04*** (0,01)
road:air	–4,00 (6,45)					
road:water	–5,28 (7,98)					
bus:water	–2,25 (8,93)					
bus:road	–3,04 (8,10)				0,05*** (0,01)	
bus:air:road			0,008*** (0,002)			
bus:air:water	0,59 (1,53)					
bus:road:air	0,81 (1,40)					
bus:road:water	1,04 (1,73)					
road:air:water	1,16 (1,38)					
bus:road: air:water	–0,23 (0,30)					
Константа	–12,24 (191,11)	–1,21 (0,71)	1,71*** (0,20)	–0,37 (0,65)	0,77 (0,39)	0,71 (0,39)
Характеристики моделей						
θ (s.e.)	6,45 (1,04)	5,77 (0,93)	5,46 (0,88)	5,73 (0,92)	5,52 (0,89)	5,45 (0,88)
deviance (null)	121,57	108,85	102,86	107,95	104,10	102,73
d.f. (null)	72	72	72	72	72	72
deviance	74,88	75,10	75,22	75,11	75,19	75,22
d.f.	57	69	71	70	70	70
LR	–731,96	–736,22	–738,40	–736,54	–737,94	–738,45
AIC	1497,92	1482,43	1482,81	1481,07	1483,88	1484,90

* – p < 0,05; ** – p < 0,005, *** – p < 0,001; Сокращения: b – коэффициент регрессии, s.e. – стандартная ошибка, θ – параметр распределения, deviance – девианс, d.f. – степени свободы, null – нуль-значение, LR – логарифм максимального правдоподобия, AIC – информационный критерий Акаике, p – вероятность ошибки первого рода.

трении происходит разогрев трущихся поверхностей, вследствие чего образуется большое количество мелких частиц сопряжения.

Автобусы занимают в этом смысле особое положение. В силу специфики эксплуатации им надо часто тормозить, у них большие шинные протекторы, и они имеют наиболее тесный контакт с твердым покрытием асфальтовых дорог. При работе автобусов образуется огромное количество ТПЧ различного диаметра [7]. Твердое покрытие – это прежде всего асфальт. Асфальт состоит из смеси битумов с минеральными материалами: гравием и песком (щебнем или гравием, песком и минеральным порошком в искусственном асфальте). Асфальтобетонная смесь – это строительный материал в виде уплотненной смеси щебня, песка, минерального порошка и битума. При эксплуатации автотранспорта на дорогах с асфальтовым покрытием температура контакта достигает 40 °С и выше и увеличивается при резком торможении или наоборот при резком нажатии педали газа. Таким образом и происходит образование и формирование ТПЧ [4, 5].

Развитие АДК приводит в зоне его влияния к изменениям профиля загрязнения окружающей среды, в том числе появлению соединений тяжелых металлов и полициклических ароматических углеводородов в составе ТПЧ разного диаметра [24, 25], которые образуются не только в результате сгорания топлива, но также в ходе эксплуатационного износа дорожного покрытия, тормозной системы и шин, протекторов, в зависимости от типа автомобильного транспорта [5, 7, 12, 19].

Данные литературы свидетельствуют о том, что аэрополлютанты в виде ТПЧ, в частности – содержащие кремний, алюминий, свинец и др. – особенно если действуют на формирующийся организм с детства, не только способны нарушить развитие легких и дыхательной функции, но и производят системные, в том числе опосредованные через пищу и кишечную микробиоту, эффекты в других органах, вплоть до нарушения психомоторного развития и иммунитета [9, 20, 28, 29, 34, 36]. Механизмы возможного влияния аэрополлютантов на аутоиммунитет могут быть разными: адъювантоподобное действие, индукция таких модификаций антигенов, к которым не толерантны лимфоциты организма, появление неоантигенов в результате действия активных кислород- и галогенсодержащих радикалов и иных медиаторов воспаления [3, 30] и пр. Эффекты при этом могут быть разнонаправленными и нетривиальными: так, недавно в Германии была показана обратная связь между степенью экспозиции озоновому загрязнению и среднесрочной метаболической декомпенсацией СД1, оцененной по количеству гликированного гемоглобина [40]. Ранее ряд авторов, в частности, в Германии, Канаде и Италии, находили связь СД1 с загрязнением атмосферы или сообщали об отягощении течения этого заболевания при аэрополлюции [23, 25, 27]. Сообщалось о том, что атмосферные загрязнения особенно существенно влияли на развитие СД1, если их действие приходилось на ранний детский возраст или интранатальный период [32, 35, 38]. В недавних (2018 г.) исследованиях польских авторов были показаны различия по заболеваемости СД1 типа в зависимости от сельского или городского проживания, в последнем случае заболеваемость была гораздо выше [49, 50].

В свете вышеприведенных данных понятны и выявленные нами достоверный мультипликативный эффект загрязненности воздуха и количества автобусов и аддитивный эффект географической плотности сети автомобильных дорог на заболеваемость СД1.

Заключение

Показано влияние урбанистических факторов на возникновение СД1 у населения РФ.

Существенные факторы, способствующие заболеваемости СД1, связаны с АДК – географической плотностью сети автомобильных дорог с твердым покрытием и относительным количеством автобусов в регионе. Мультипликативное к ним влияние на заболеваемость СД1 оказывают выбросы загрязняющих веществ в атмосферный воздух.

Для раскрытия механизмов участия антропогенных факторов в патогенезе аутоиммунного поражения островковых В-клеток при развитии СД1 требуется экспериментальное моделирование действия ТПЧ на панкреатические островки подопытных животных. По данным литературы, у мышей экспериментальный СД1 и аэрополлютанты дизельного топлива оказывают взаимно отягощающее влияние на поражение бронхолегочного аппарата и панкреатических островков [40, 41].

Факторы урбанизации являются контролируемыми, и, следовательно, многие из этих неблагоприятных последствий для здоровья могут быть предотвращены. В дальнейшем необходимо изучить медицинскую географию других аутоиммунных болезней в контексте влияния региональных факторов, связанных с урбанизацией.

Уведомление

Авторы внесли следующий вклад в работу: Л.А. Сопрун – анализ эпидемиолого-географических источников, подсчеты, написание текста; А.Н. Гвоздецкий – математическая обработка данных; И.М. Акулин – анализ эпидемиологической литературы; В.И. Утехин – редактирование текста; Л.П. Чурилов – идея и дизайн исследования, анализ литературы по патологии, руководство работой группы.

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К 90-ЛЕТНЕМУ ЮБИЛЕЮ МАРГАРИТЫ ДМИТРИЕВНЫ УФИМЦЕВОЙ

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Маргарита Дмитриевна Уфимцева

2018 год – юбилейный для Маргариты Дмитриевны Уфимцевой, крупнейшего российского специалиста в области биогеохимии растений.

М.Д. Уфимцева родилась 16 декабря 1928 г. в г. Сим Челябинской области. Еще учась в школе, она самостоятельно определила место своей дальнейшей учебы и в 1946 г. приехала в послевоенный Ленинград поступать на географический факультет Ленинградского государственного университета. Уже тогда она знала, что будет учиться на кафедре ботанической географии. В 1951 г. Маргарита Уфимцева окончила эту кафедру с отличием и была рекомендована в аспирантуру. Ее руководителем был заведующий кафедрой проф. А.А. Корчагин. Кандидатская диссертация была посвящена исследованию растительности степного Крыма в связи со строительством Северо-Крымского канала по заданию крымских областных организаций и Гипроводхлопка. Строительство началось в 1952 г. Совместно с почвоведом Н.Н. Дзенс-Литовской М.Д. Уфимцева приняла участие в составлении крупномасштабных карт растительности и почв территории строительства. Защитив в 1954 г. кандидатскую диссертацию «Изучение и картирование растительности степного Крыма», М.Д. Уфимцева начала работу на кафедре в должности ассистента. В 1965 г. была избрана доцентом по конкурсу, а в 1966 г. утверждена в ученом звании доцента. Маргариту Дмитриевну связывают с Санкт-Петербургским (Ленинградским) государственным университетом почти 60 лет, из них 50 лет – с кафедрой ботанической географии географического факультета, где она проработала до 1996 г.

За свою многолетнюю педагогическую работу Маргарита Дмитриевна разработала и прочитала 16 курсов: «Ботаническая география», «Биогеоценология», «Методы ботанико-географических исследований», «Растительные сообщества», «Ботаническая география СССР», «Геохимическая экология растений», «Фитоиндикаторы», «Систематика высших растений», «Учение о биосфере» и др. К своим курсам она всегда относилась крайне ответственно.

Мария Дмитриевна – прирожденный педагог, и со студентами у нее всегда складывались прекрасные отношения, несмотря на ее высокую требовательность (некоторым студентам приходилось для сдачи экзамена или получения зачета встречаться с М.Д. несколько раз). Она постоянно заботилась о студентах, вникала в их проблемы и старалась, по возможности, помочь, учила студентов не только специальности, но и главному – отношению к труду. К каждой курсовой она относилась как к серьезной научной работе, помногу раз вычитывала их, оттачивала с автором каждую фразу. Выполненные под ее руководством работы студентов были награждены медалями и дипломами I и II степеней на городских и Всесоюзных конкурсах.

Начиная с аспирантских лет, М.Д. Уфимцева вела учебную и производственную полевые практики студентов, а впоследствии была руководителем практик. Она проводила практику не только с ботанико-географами, но и со студентами других кафедр – океанологами, климатологами, геоморфологами и др. И ко всем была одинаково требовательна, желая научить их понимать закономерности природы. Маргарита Дмитриевна отличалась удивительной неутомимостью: рабочий день начинался в 8–9 часов, заканчивался в 21–22 часа. Весь день она была со студентами: читала лекции, проводила экскурсии, определяла растения, занималась проверкой работы бригад (а бригады тогда были по два человека). Такая выносливость постоянно поддерживалась занятиями спортом: сперва она занималась спортивной гимнастикой, выступала за команду университета на разных соревнованиях, затем переключилась на аэробику.

В 1968 г. М.Д. Уфимцева опубликовала «Краткое руководство по проведению летней учебной практики по ботанической географии», которое до сих пор является прекрасным учебным пособием по проведению летней практики по ботанической географии на факультете, и не одно поколение с помощью этой работы получило свои базовые знания.

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Многие годы Маргарита Дмитриевна курировала студенческий научный кружок кафедры, в котором участвовали студенты всех курсов. В этот период жизнь кружка била ключом, энтузиазм куратора зажигал студентов: они делали интересные доклады о практиках, обсуждали серьезные теоретические проблемы.

М.Д. Уфимцева непрерывно работала над повышением своей квалификации, расширяла знания в области ботаники, ботанической географии, почвоведения, почвенного анализа, постоянно занималась научной работой, участвуя в многочисленных экспедициях и публикуя статьи. Во всех ее работах чувствуется глубокое знание материала, четкость в изложении мысли, глубина раскрытия темы.

Первые научные исследования М.Д. Уфимцевой были связаны с изучением растительности степного Крыма, впоследствии, под влиянием яркого человека и выдающегося ученого доктора геолого-минералогических наук Михаила Михайловича Ермолаева, Маргарита Дмитриевна увлеклась биогеохимией, которая стала ее призванием. В 1963 г. вышла из печати ее первая публикация по этому научному направлению: «Биогеохимические исследования и индикаторная роль растительности при поисках полезных ископаемых на Южном Урале». Она проводила научную работу по биогеохимическим поискам полезных ископаемых в Приладожье, Карелии, на Кольском полуострове, Тимане, в Оренбургской области. Ее исследования в области биогеохимии растений, геохимической экологии и разработки биогеохимических поисков полезных ископаемых получили высокую оценку в научных кругах. Как крупный специалист в этой области она входила в состав Научного совета АН СССР по проблемам микроэлементов в биологии и была членом одной из секций Межведомственного научно-технического совета по комплексным проблемам охраны окружающей природной среды и рационального использования природных ресурсов при Государственном комитете СССР по науке и технике.

М.Д. Уфимцева – один из создателей Санкт-Петербургской биогеохимической школы, признанной в научных кругах нашей страны и за рубежом. Под ее руководством написаны и успешно защищены кандидатские диссертации Н.С. Шиховой, М.Г. Опекуновой, Д.В. Московченко, Н.В. Терехиной, С.А. Банарь – специалистов, работающих ныне в разных концах России.

Все время работы на факультете М.Д. проводила активную общественную деятельность: являлась членом методической комиссии факультета, председателем группы Народного контроля факультета, а с 1980 г. возглавляла оргкомиссию при комитете Народного контроля ЛГУ. Она также являлась председателем первичной организации общества «Знание» на географическом факультете. Долгие годы была заместителем председателя Совета по экологическому просвещению при правлении Всероссийского общества охраны природы, деканом общественного экологического факультета при Доме научно-технической пропаганды. В течение длительного времени была бессменным секретарем философского семинара для преподавателей факультета, правой рукой его руководителя профессора О.А. Дроздова. Проводила очень интересные заседания, организовывала научно-философские доклады. Не без ее деятельного участия эти семинары проходили не формально, а бурно и интересно.

С 1991 по 2004 г. М.Д. Уфимцева была старшим научным сотрудником в НИИ земной коры им. акад. Ф.Ю. Левинсона-Лессинга СПбГУ, где вела не только научную работу, но и полевые исследования со студентами и руководила курсовыми и дипломными работами студентов на кафедре экологической геологии геологического факультета СПбГУ.

В 2000 г. М.Д. проводила комплексные эколого-биогеохимические исследования в зоне техногенного воздействия медно-никелевого горно-металлургического комбината «Никель» ОАО «ГМК Печенганикель». Результаты опубликованы в работе «Экологическое состояние озера Куэтсъярви и прилегающей территории» (СПб., 2003).

Начиная с конца 1980-х одним из направлений научной деятельности М.Д. является экофитоиндикация в связи с оценкой экологического состояния городской среды на примерах отдельных районов Санкт-Петербурга. На основании собранных материалов в соавторстве с Терехиной Н.В. была издана монография «Фитоиндикация экологического состояния урбогеосистем Санкт-Петербурга» (2005).

После ухода из университета Маргарита Дмитриевна продолжает вести активную научную жизнь. Она выступает с докладами на российских и международных симпозиумах и конференциях по биогеохимии, геохимии, дистанционным методам исследования (Москва, 2013, 2016; Санкт-Петербург, 2018; Вена, 2015, 2018). Она читает лекции по фитоиндикации, участвует в жюри при проведении городских и областных олимпиад по экологии, является членом редколлегии журнала «Биосфера», к ней обращаются за помощью и консультацией студенты и коллеги.

М.Д. Уфимцевой опубликовано более 100 научных работ, 3 монографии, 2 учебных пособия, 1 учебник. В 2012 г. она получила Благодарность от Института геохимии и аналитической химии им. В.И. Вернадского за фундаментальный вклад в развитие биогеохимии и геохимической экологии растений с вручением памятной медали Виктора Владиславовича Ковальского.

Маргарита Дмитриевна увлечена не только научно-педагогической деятельностью – она всегда живо интересовалась и интересуется литературой, постоянно ходит на концерты классической музыки и любимых артистов, всю жизнь увлекается балетом.

Мы желаем Маргарите Дмитриевне крепкого здоровья, жизненного оптимизма и дальнейших творческих успехов!

СВЕДЕНИЯ ОБ АВТОРАХ

АКУЛИН
ИГОРЬ МИХАЙЛОВИЧ,
доктор медицинских наук, профессор, заведующий кафедрой организации здравоохранения и медицинского права юридического факультета Санкт-Петербургского государственного университета (СПбГУ). Окончил Курский государственный медицинский институт в 1973 г. по специальности «лечебное дело». В 1996 г. получил второе высшее образование в СПбГУ на юридическом факультете по специальности «юриспруденция». В 1973–1974 гг. начал трудовую деятельность в Ленинградском институте усовершенствования врачей-экспертов на должности невропатолога-эксперта. В 1974–1975 гг. работал в Брянской областной врачебно-трудовой экспертной комиссии. В 1991–1996 гг. стал заместителем начальника управления амбулаторной базы, начальником управления перспективного развития здравоохранения, начальником амбулаторной базы, отвечал за организацию обязательного медицинского страхования, первичную медико-социальную помощь в Комитете по здравоохранению Санкт-Петербурга. С 1996 г. занимал должность заместителя Председателя Комитета по здравоохранению Правительства Санкт-Петербурга. Под его руководством была реализована Программа развития общеврачебной практики, обязательного медицинского страхования. Преподавательскую деятельность начал в 1996 г. доцентом кафедры семейной медицины МАПО. С 1998 г. по настоящее время работает в СПбГУ на юридическом факультете, где организовал и возглавил магистерскую программу по медицинскому праву и фармацевтическому праву. Является Председателем Правления Ассоциации медицинского права Санкт-Петербурга, Председателем Третейского суда по медицинскому страхованию и здравоохранению при Торгово-промышленной палате Санкт-Петербурга, членом Консультативного Совета при Уполномоченном по правам человека в Санкт-Петербурге. Опубликовал более 110 научных трудов, 5 учебно-методических пособий, соавтор учебника по правоведению. Подготовил 2 кандидатов медицинских наук, 29 магистров и дипломников по специализации «медицинское право». Научные интересы включают вопросы медицинского права, общеврачебную практику, семейную медицину, промышленную медицину.

ГВОЗДЕЦКИЙ
АНТОН НИКОЛАЕВИЧ,
врач-психиатр Городской психиатрической больницы № 7 имени акад. И.П. Павлова (Санкт-Петербург), аспирант кафедры психиатрии и наркологии Санкт-Петербургского государственного университета (СПбГУ). Окончил СПбГУ в 2014 г. по специальности «лечебное дело». В 2016 г. получил сертификат специалиста по специальности «психиатрия». Научные интересы: биомедицинская статистика, доказательная медицина и воспроизводимые биомедицинские исследования, психиатрия, медицинское право и этика, организация психиатрической помощи, математическое моделирование психических процессов. Опубликовал более 30 научных работ.

ГЕРАСИМОВ
АЛЕКСАНДР ОЛЕГОВИЧ,
кандидат биологических наук, старший научный сотрудник лаборатории методов реабилитации техногенных ландшафтов Санкт-Петербургского научно-исследовательского центра экологической безопасности РАН. Родился в 1975 г. в Ленинграде. В 1999 г. окончил Лесохозяйственный факультет Лесотехнической академии, в 2003 г. защитил кандидатскую диссертацию по теме «Устойчивость хвойных пород в уличных посадках Санкт-Петербурга» в Научно-исследовательском институте лесного хозяйства. Область научных интересов: экология и охрана окружающей среды. Автор более чем 50 научных публикаций.

СОПРУН
ЛИДИЯ АЛЕКСАНДРОВНА,
кандидат медицинских наук, ассистент кафедры организации здравоохранения и медицинского права Санкт-Петербургского государственного университета (СПбГУ). В 2009 г. окончила медико-профилактический факультет Оренбургской государственной медицинской академии. В 2009–2010 гг. училась в клинической интернатуре по общей гигиене, а в 2010–2011 гг. – в клинической интернату-

ре по эпидемиологии на базе Медицинской академии последипломного образования (Санкт-Петербург) на кафедре медицинской экологии и эпидемиологии им. Г.В. Хлопина. В СПбГУ преподает с 2013 г. Соавтор рабочих программ дисциплин «гигиена» и «гигиена, основы экологии человека, военная гигиена» для студентов медицинского факультета и факультета стоматологии и медицинских технологий. Направления научных интересов: больничная гигиена, эпидемиология гемоконтактных инфекций, медицинские отходы. Опубликовала более 30 научных работ. Участница программы японо-российских молодежных обменов в области региональной медицины.

УТЕХИН
ВЛАДИМИР ИОСИФОВИЧ,
кандидат медицинских наук, доцент кафедры патологии Санкт-Петербургского государственного университета и кафедры патофизиологии с курсом иммунопатологии Санкт-Петербургского государственного первого медицинского университета (СПбГПМУ). Окончил Ленинградский санитарно-гигиенический медицинский институт (ЛСГМИ) в 1970 г. Научную работу начинал как младший научный сотрудник ЛСГМИ с 1970 по 1981 г. С 1981 по 2004 г. – ассистент, а с 1985 г. – доцент кафедры патофизиологии СПбГПМУ. Научные интересы: патология эндокринной системы, иммунопатология, диабетология, электронная микроскопия, морфологические и иммуноморфологические методы исследований, экологическая медицина. В 1990-х гг. участвовал в медико-экологических экспедициях в регионы Белоруссии и Урала, пострадавшие от радионуклидного загрязнения в результате техногенных катастроф. С 2004 г. – штатный сотрудник кафедры патологии СПбГУ. Автор 120 научных работ, соавтор глав в учебниках и монографиях по патофизиологии и истории медицины, популярных книг по клеточной биологии.

ЧУГУНОВА
МАРИНА ВАЛЕНТИНОВНА,
кандидат биологических наук, старший научный сотрудник Лаборатории методов реабилитации техногенных ландшафтов Санкт-Петербургского научно-исследовательского центра экологической безопасности РАН (ЦИНЭБ РАН). Родилась в 1954 г. в Ленинграде. В 1976 г. с отличием окончила биолого-почвенный факультет Ленинградского государственного университета им. А.А. Жданова по специальности «почвоведение-агрохимия». В 1989 г. защитила кандидатскую диссертацию на тему: «Влияние тяжелых металлов на почвенные микробиоценозы и их функционирование». В НИЦЭБ РАН работает с 2000 г. Сфера научных интересов: экология почвенных микроорганизмов и охрана окружающей среды. Автор более чем 100 научных трудов.

ЧУРИЛОВ
ЛЕОНИД ПАВЛОВИЧ,
кандидат медицинских наук, доцент, заведующий кафедрой патологии, заместитель руководителя лаборатории мозаики аутоиммунитета Санкт-Петербургского государственного университета (СПбГУ). Окончил в 1979 г. Ленинградский педиатрический медицинский институт и в 1984 г. аспирантуру по патофизиологии. Области научных интересов: иммуноэндокринология, патофизиология, медицинская экология, фтизиопульмонология, история медицины и биоэтика, методология медицинского образования. Внес значительный вклад в развитие теории иммуноглобулиновой регуляции генетически детерминированных клеточных функций и концепции трансформации гипоталамического синдрома пубертатного периода в ранний осложненный метаболический синдром. Участвовал в медико-экологических экспедициях в районы, пострадавшие от техногенных ядерных аварий. Автор или соавтор около 700 научных трудов, в том числе более 30 монографий, руководств и учебников по патофизиологии, иммунологии и эндокринологии, истории медицины. Автор учебного комплекса «Патофизиология», включающего трехтомный учебник, словарь, компакт-диск, пособие для стоматологического факультета, комплект учебных плакатов, словарь и практикум. Один из разработчиков и декан первой в истории образования России российско-американской программы англоязычного медицинского обучения (1993–1998), за вклад в развитие которой удостоен почетного диплома Сената штата Нью-Йорк (1994). Член Центральной учебно-методической комиссии Учебно-методического объединения медицинских и фармацевтических вузов России по патофизиологии. Лауреат II Всесоюзного конкурса на лучшее исследование по патофизиологии (1987), премии V Всемирного конгресса патофизиологов в Пекине (2006), премии СПбГУ «За педагогическое мастерство» (2012). Награжден почетными грамотами СПбГУ и Минобразования РФ, грамотами и медалями Общества патофизиологов, Санкт-Петербургской духовной семинарии, а также ряда гражданских и военных университетов Китая. Член Санкт-Петербургского отделения Международного общества патофизиологов, Санкт-Петербургского общества историков медицины, редколлегий журналов «Биосфера», «Autoimmunity Reviews», «Biomedical research and Clinical Communications», «Russian Biomedical Research», «Open Journal of Pathology», «Клиническая патофизиология», ежегодников «Бюлетень читань ім. В.В. Підвисоцького» (Украина), «Здоровье – основа человеческого потенциала: проблемы и пути их решения»; почетный иностранный член правления Общества патофизиологов Украины.

БЛАГОДАРНОСТЬ РЕЦЕНЗЕНТАМ

Редакция журнала «Биосфера» и руководство ФНИ «XXI век» считают рецензирование рукописей важнейшим условием работы научных журналов и выражают глубокую признательность специалистам, согласившимся помочь редколлегии в 2018 г.:

Анисимов М.А.	канд. геогр. наук, старший научный сотрудник отдела географии полярных стран Арктического и Антарктического научно-исследовательского института, старший преподаватель кафедры физической географии и ландшафтного планирования Института наук о Земле Санкт-Петербургского государственного университета
Архипченко И.А.	докт. биол. наук, ведущий научный сотрудник Всероссийского научно-исследовательского института сельскохозяйственной микробиологии (Санкт-Петербург)
Большиянов Д.Ю.	докт. геогр. наук, ведущий научный сотрудник отдела географии полярных стран Арктического и Антарктического научно-исследовательского института (Санкт-Петербург)
Вилкова Н.А.	докт. с.-х. наук, главный научный сотрудник Всероссийского научно-исследовательского института защиты растений (Санкт-Петербург)
Гордышевский С.М.	председатель правления НП «Экологический союз», председатель комитета по экологической, промышленной и технологической безопасности Союза промышленников и предпринимателей Санкт-Петербурга
Грачева В.С.	канд. биол. наук, доцент кафедры генетики, разведения и биотехнологии животных факультета зооинженерии и биотехнологий Санкт-Петербургского государственного аграрного университета
Егоров А.А.	канд. биол. наук, заведующий кафедрой биогеографии и охраны природы Института наук о Земле Санкт-Петербургского государственного университета
Жариков Ю.Г.	докт. юр. наук, главный научный сотрудник отдела природоресурсного законодательства Институт законодательства и сравнительного правоведения при Правительстве РФ (Москва)
Ингель Ф.И.	докт. биол. наук, и. о. заведующего лабораторией генетической токсикологии Центра стратегического планирования Министерства здравоохранения РФ (Москва)
Кашин С.В.	канд. геол.-мин. наук, ведущий научный сотрудник отдела металлогении и геологии месторождений полезных ископаемых Всероссийского научно-исследовательского геологического института им. А.П. Карпинского (Санкт-Петербург)
Коржевский Д.Э.	докт. мед. наук, профессор кафедры фундаментальных проблем медицины и медицинских технологии факультета стоматологии и медицинских технологий Санкт-Петербургского государственного университета
Коровин А.Е.	докт. мед. наук, начальник научно-исследовательской лаборатории (военной терапии) научно-исследовательского отдела (экспериментальной медицины) научно-исследовательского центра Военно-медицинской академии им. С.М. Кирова (Санкт-Петербург)
Мирин Д.М.	канд. биол. наук, заведующий кафедрой геоботаники и экологии растений биологического факультета Санкт-Петербургского государственного университета
Москаленко В.А.	канд. техн. наук, старший научный сотрудник, ведущий специалист по проблемам экологии и безопасности Городского центра экспертиз (Санкт-Петербург)
Мыльников С.В.	канд. биол. наук, доцент кафедры генетики и биотехнологии биологического факультета Санкт-Петербургского государственного университета
Надпорожская М.А.	канд. с.-х. наук, доцент кафедры агрохимии биологического факультета Санкт-Петербургского государственного университета
Новикова Е.А.	канд. биол. наук, доцент кафедры прикладной экологии биологического факультета Санкт-Петербургского государственного университета
Савостьянов Г.А.	канд. мед наук, докт. биол. наук, ведущий научный сотрудник НИИ эволюционной физиологии и биохимии им. И.М. Сеченова РАН, Санкт-Петербург
Синявина Н.Г.	канд. биол. наук, старший научный сотрудник отдела светофизиологии растений и биопродуктивности агроэкосистем Агрофизического научно-исследовательского института (Санкт-Петербург)
Сухорученко Г.И.	докт. с.-х. наук, главный научный сотрудник Всероссийского научно-исследовательского института защиты растений (Санкт-Петербург)
Шарова Е.И.	канд. биол. наук, доцент кафедры физиологии и биохимии растений биологического факультета Санкт-Петербургского государственного университета
Шустов М.В.	докт. биол. наук, заведующий отделом флоры Главного ботанического сада им. Н.В. Цицина РАН (Москва)

СВОДНОЕ СОДЕРЖАНИЕ ТОМА 10
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От редакции:

В первом номере «Биосферы» за 2018 г. было опубликовано решение издателя журнала (Фонд научных исследований «XXI век») и редакции[1] о возможности дополнять статьи, находящиеся на открытом доступе на сайте журнала, переводами на английский с сохранением тех же DOI, что и у оригинальных русскоязычных версий. При этом цитирование переводов предусматривает отсылку к выходным данным оригинальных версий, которые по прежнему должны быть снабжены всеми метаданными (название, авторы, их место работы, список литературы) на английском. Таким образом полное содержание статей может быть включено в международную научную информационную среду и стать видимым для всех, кто заинтересуется им, например, в результате поиска информации через Google Scholar (Академия Гугл) – свободно доступный аналог Scopus и Web of Science, позволяющий, среди прочего, отслеживать цитирование. Публикация на английском, как и на русском, остается для авторов бесплатной, но перевод авторы либо оплачивают, если он осуществляется силами редакции, либо предоставляют свой (или выполненный по заказу сторонним переводчикам), но такой, чтобы он удовлетворял хотя бы минимальным требованиям к соблюдению грамматики и соответствию смысла перевода исходному тексту. Однако практика работы с авторскими переводами рефератов показывает, что практически всегда требуется редактирование, сопоставимое по объему работы с переводом заново. Поэтому редакция оставляет за собой право отказывать в публикации переводов, признанных непригодными к тому, чтобы их показывать. Бесплатным редакционным переводом предполагается поощрять авторов одной-двух статей в год, признанных редакцией с учетом мнения редколлегии наиболее интересными для международной аудитории. Первые результаты этого нововведения публикуются с этом номере, последнем в 2018 г.

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[1] Редакционная статья. Об изменениях в редколлегии и редакционной политике журнала «Биосфера». Биосфера. 2018;9(1):A5.

DECENTRALIZED ORGANISM EXEMPLIFIED WITH COLONIAL HYDROID SPECIES

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Colonial hydroids, corals, bryozoans, ascidia, and some other aqueous species look as numerous interconnected bodies. However, they are not communities; rather, they are manifold individuals adapted to capturing food particles from flowing water, which is what makes them looking similar to plants organized to capture sunlight. The colonial type of organization is believed to emerge as the result of an incomplete vegetative proliferation associated with that young unit bodies stay connected with their mother. Such manifold or modular organisms are less integrated or centralized compared with their solitary (unitary) ancestors. The structure of such decentralized organisms provide opportunities to study the integration of parts into a whole involving no central organizers. Such relationships between a whole and its parts are featured by many natural and social systems but are still poorly studied. The specialized organizing means, such as the nervous and endocrine systems, are but superstructures built upon the more simple way of inner coordination featured by decentralized organisms whose integrity is based on interactions between numerous equipotent parts. Among the decentralized organisms, colonial hydroids are most convenient for studying and thus may serve as paragons of the decentralized biological organization as such. The salient features of the decentralized organization are: multiplication or polymerization of parts; the absence of regulatory organs; a significance degree of self-sufficiency of parts; a high resistance of the whole to impacts on its part; the plasticity of the shape and a broad variation of the sizes of the whole; ingrowth into the environment; network organization; a cyclic mode of morphogenesis; and indeterminacy of age limits. The implications of the results obtained in studying decentralized organisms for supra-organismal systems, such as populations, ecosystems, or biosphere, are discussed.

***Keywords**: colonial organism; Hydrozoa, modular organization; decentralized system.*

INTRODUCTION

Centralized, Non-Centralized and Decentralized Systems

The two alternatives of system organization, centralized and non-centralized, have been avidly discussed in the scientific literature for more than half a century, but mainly with regard to the social systems, collective management bodies, economy, and information flows, without even minor attempts of system-wide generalizations [67, 98, 138, 153, 162]. However, the conceptual possibilities to analyze the degrees of centralization are much broader, and they can be applied to any systems, including biological ones [148].

The two opposite ways of organizing a complex system are centralization and decentralization.

Centralization means strengthening the role of a coordinating center, i.e. increasing the coherence of processes within a system and their subordination to a certain order or certain signals. This is associated with the specialization of the parts and processes within a system, the restriction of freedom of the parts, and the reduction of uncertainty, both functional and structural, within the system.

Decentralization is increasing the independence of system parts and parallel processes, decreasing the frequency of commands from a center (if it exists), enhancing the variability of the whole and the uncertainty of all its features and, ultimately, making the algorithms of vital processes more flexible.

The decentralized system concept is often applied in the literature to non-centralized systems. However, it is reasonable to distinguish the two types of systems according to their origins. In the first of the types, all elements of a system are the parts of a single organism, which are not disengaged because they have originated from a single “root”, as e.g. zooids in a colonial organism. The non-centralized systems that result from decentralization may be called decentralized systems. In the second type, a system is composed of heterogeneous elements, which originate, e.g., from independent organisms of the same species or even different species. Such systems are non-centralized by their origin; they have not been decentralized, i.e., did not undergo a reduction in the degree of their centralization. Differences in the degrees of keenness affect the degrees of integrity of systems and the modes of their self-organization; however, the present article is not concerned with that. Therefore, we will use the terms “decentralized” and “non-centralized” as synonyms, although their scopes are different. The concept of “non-centralized” organization is broader than that of “decentralized” organization, the latter being a particular case of the former. With all that, the present paper mostly addresses their common features as they may be exemplified with decentralized systems.

Non-centralized systems, including decentralized systems, are entities that consist of interacting parts whose functions are not controlled by any individual specific body.

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In any natural system, there are signs of centralization and decentralization. The least centralized biological systems are ecosystems, and the most centralized ones are organisms. The simultaneous effect of the environment on all ecosystem components is an analogue of the centralized regulation. Such "control" has very little in common with the internal regulation carried out by the nervous system of multicellular organisms.

The non-centralized mode of integration appears to be inherent in all natural systems and makes the base of their integrity. However, centralization imposes significant constraints on the manifestations of the non-centralized integration.

Rigid control mechanisms have long attracted much more attention of researchers than coordination mechanisms based on the freedom of the parts (components) of a system. In recent decades, the situation has begun to change due to studies and conceptual generalizations related to the non-centralized organization of complex social, biological and technical systems [52, 53, 65, 83, 120, 121]. Knowing the optimal relationships between centralization and freedom is especially in demand in politics, economics, state security, sociology, pedagogy, etc. [81, 92, 143]. This is what makes it important to study other systems based solely on non-centralized coordination.

Decentralized Organisms

In a non-centralized organism, no central control organ is responsible for coordinating the processes that take place in its various parts. The integrity of such an organism is ensured only by the unity of its body, in which all its parts have the same origin, such as a fertilized egg or a fragment of the parent organism, while differentiation and specialization are achieved automatically due to the so-called "positional information", i.e., responses to the specific positions of the emerging parts of a developing body relative to the rest of the body and to the environment [70, 82, 159].

The central control organs include the nervous and endocrine systems. Hence, fungi, plants and animals that lack neuroendocrine regulation can be referred to non-centralized organisms.

The lack of the centralized management of vital activities is especially apparent in the so-called modular organisms, which will be discussed in the next section. They have undergone genuine decentralization, i.e., transition from the centralized organization to the non-centralized one. The centralized organization is featured by unitary (non-colonial) organisms, e.g., hydra or actinia, whereas vegetative reproduction not associated with the separation of individuals results in the decentralized organization (Fig. 1).

The nervous system of a hydra or actinia is underdeveloped, but is sufficient to control the movements of an individual. For example, a hydra or actinia reacts to irritation by shortening its body length and contracting its tentacles. Similar responses are observed in the individual hydranths of a colonial organism. However, in many colonial species, a hydranth does not influence its neighbors [99].

Modular Organisms

All organisms can be referred to the categories of unitary and modular [76, 119, 139].

A unitary organism is characterized by a specific shape and size of its body, minimal variations in its individual development, and a limited number of repetitive organs or parts of its body.

A modular organism is characterized by multiple repeats of its body parts due to a special form of its individual development, which involves *morphogenetic cycles that results in the* polymerization of its organs, the absence of non-repeated (singular) parts able to function as operating organs, and a highly variable body shape and size [35, 39, 48].

In both cases, the individual development starts from a single source, i.e., a fertilized ovum whose division produces a multicellular organism or, upon the asexual reproduction (division, budding, parthenogenesis), from a part of a single initial (maternal) organism. At the early stages of ontogenesis, the unitary and modular organisms are similar by their organization. However, after their individual ontogenies are completed, their subsequent developmental pathways diverse. The modular organisms under favorable conditions can grow indefinitely by reproducing their individual parts: they ramify and form branched or monolithic bodies, which can later disintegrate or retain their integrity. Such unlimited growth is a feature of primitive organization.

At difference from the modular organisms, the unitary ones slow down their growth rate as they age, and the shapes of not only their individual parts, but also their whole bodies become strictly defined[1]. Any constraints imposed on morphogenesis is a manifestation of increasing the complexity of the respective development program. Unitary and modular organisms may relate to the same taxonomic unit. Since the module of an invertebrate animal often resembles a unitary organism, it is believed that unitary organisms are primary, and colonial ones (which are essentially modular) are secondary. If this is so, this means that the formation of a colonial organism is associated with decentralization.

The modular organization is widespread in wildlife. Fungi, many plants and many colonial invertebrates are modular [35, 48, 119]. Sponges, corals, hydroids[2], bryozoans, camptozoids,

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[1] There are numerous examples of growth during virtually the whole life of a unitary organism, but growth gradually slows down in each of such cases, which is not typical of modular organisms.

[2] Although included into the class Hydrozoa, siphonophores do conform to characteristics of a modular body, except for that: (1) they have a non-polymerized organ, i.e. pneumatophore, (2) their stolon virtually does not branch; (3) there exists a common, albeit underdeveloped, colonial ner-

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and ascidians represent the contemporary fauna. Modular organisms are a convenient object for studying the characteristic features of decentralization, as well as the regularities of biological systems integrity [35, 49-51, 125].

Decentralization as a Consequence of the Modular Organization

Multiplication of all body parts and the absence of a coordinating organ result in the genuine decentralization, i.e., not just the absence or underdevelopment of a central control system, but the complete elimination of such coordination between modules. "Rudiments" of possible coordination remain in individual modules. This phenomenon can be illustrated with unitary and colonial Cnidarian species. There is a cluster of nerve cells around the oral opening of a hydra or actinia, and the movements of its tentacles, body and mouth are coordinated in some cases. By contrast, colonial hydroids and six-ray corals feature no coordination between zooids, while in their common body (cenosarcum), nerve cells are scattered and do not form plexuses[3].

The individual development clearly shows the stages of transition from a singular species to a colonial one. At all of the stages, the maternal entity is not accreted by a new daughter entity, but is expanded into a new structure: zooid → zooid with a protrusion of its wall → zooid with an underdeveloped daughter zooid, combined with it by their common cavity and body walls → two zooids that have retained their connection. Being multicomponent, the colonial individual loses its inherent centralization, which remains limited to only a part of its organism.

Relatively low integrity of the colonial organisms compared with the unitary ones is manifested in the ability of the former to continue normal life after losing a considerable part of the body. Unitary organisms survive in such cases due to the regeneration of the lost body part. Colonial organisms are also capable of regeneration, but they continue to function normally without it too. An organism that is modular both anatomically and functionally is simpler than a unitary one. Although it may consist of a much larger number of parts, in some cases different from each other and altered compared with a single analog, neither of the colonial organisms used above as examples has reached the degree of integration characteristic of its single analogue. This is most clearly demonstrated by the level of morphogenetic regulation, which is always higher in single organisms than in colonial ones.

Decentralization appears to be conformable to nature. Because a whole body is the sum of numerous modules that develop in accordance with the carrying capacity of their habitat, the plasticity of the shape and size of the whole body is enhanced, which may be ecologically advantageous over the strictly defined shapes and sizes of unitary organisms. The centralized control of growth and other vital functions turns out to be meaningless and even harmful in the context of adaptation of a sessile organism to an anisotropic (asymmetric) medium.

Nevertheless, there are examples of secondary centralization, e.g. in *Octocorallia*, when a colonial organism acquires an orderly organization, such as is the case of the structure of sea feathers (the order *Pennatulacea*), and becomes capable of synchronized responses of the whole body to irritation [144]. The achievement of integrity level similar to that of unitary organisms is an adaptation to specific living conditions and is rare among colonial organisms. Charles Darwin described long ago the amazing ability of sea feathers to dig themselves quickly into silted sand [11]. G. Spencer believed that in the course of phylogeny this could lead to a super-organism consisting of multicellular organisms that have undergone progressive integration along within increasing specialization of multicellular individuals comprising it [55].

Colonial Animals

Considering the decentralized organisms will be confined below to colonial organisms, most of which are invertebrates.

Organismic colonies (cormuses) or, more accurately, colonial organisms are found among metazoans, including sponges (*Porifera*), corals (*Anthozoa*), hydroids (*Hydrozoa*), bryozoans (*Bryozoa*), camptozoans (*Entoprocta*), and tunicates (*Ascidiacea* and *Thaliacea*).

Colonial hydroids are the most suitable biological model to study the non-centralized self-organization.

The objective of the present article is to sum up scattered information about functioning of colonial hydroids as decentralized organisms and to determine the possibility to extrapolate the established regularities to other non-centralized integrated systems. The article is based on studies supported by Grants Nos. 11-04-00994-a, 07-04-00736-a, 98-04-49342-a, and 95-04-12071-a from the Russian Foundation for Basic Research

The Original Studies of Decentralized Organization at the Base of the Present Discussion

Among several dozen species of colonial hydroids available for our studies, the two species most suitable for examining the patterns of decentralized organization are *Gonothyraea loveni* (Allman, 1859) and *Dynamena pumila* (L., 1758). Both species, which belong to the order Leptothecata of the class Hydrozoaof of the type Cnidaria, are

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vous system, despite the absence of an integrating organ. Nevertheless, the sum of characteristics makes it possible to regard siphonophores as modular non-centralized organisms.

[3] The only exception are siphonophores whose nervous system is developed better. Siphonophores are integration champions among modular organisms. Once, siphonophores were viewed as the crown of the evolutionary integration of a colony. However, nowadays another hypothesis is accepted: siphonophores results from neoteny, whereas their high integration is a direct consequence of the underdevelopment of their zooids and the preservation of the original integrity of the respective single organism.

referred to the two families, Campanulariidae and Sertulariidae, respectively, of highly organized animals, which differ in the morphogenetic pathways of shoot formation.

The advantages of these species as objects for studying the functioning of non-centralized colonial organisms are as the following:

– Highly transparent tissues and integuments allow examining the flows of fluids within the cavities of intact colonies, the harvesting of food particles by gastrodermal cell, the movements of specialized cells (e.g., cnidocytes), and the pulsations of cell layer.

– Growth rate is sufficient to study changes in the shape and size of a colonial organism during several days or weeks.

– The sizes of zooids, shoots and colonies make it possible to study them with conventional optical microscopes at a ×8 to ×80 magnification.

– Easy handling under laboratory conditions at temperatures 15-18 °C, which are close to the room temperature, upon feeding with *Artemia salinalarvae*.

– The ability to grow on glass plates is convenient for live colonies microscopy.

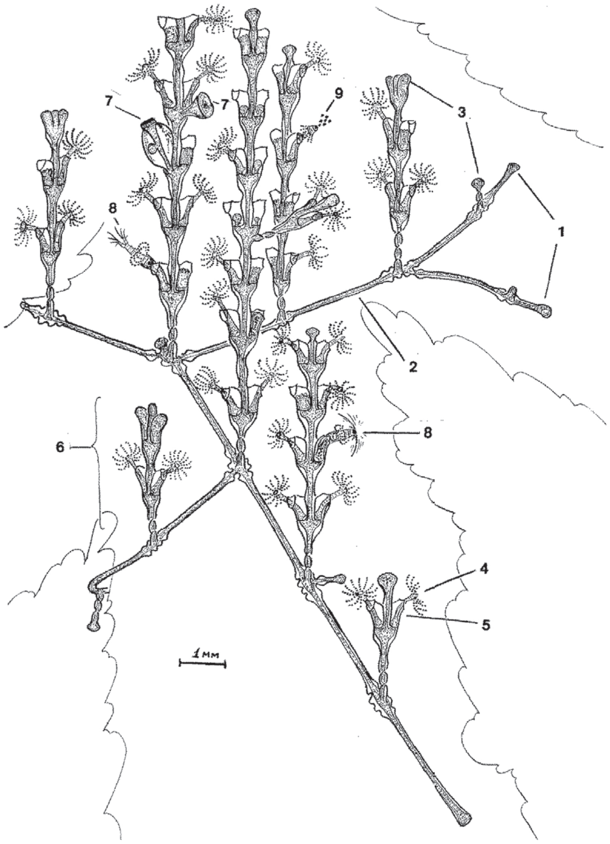

Fig. 1. A schematic drawing of the colonial hydroid *Dynamena pumila* (L.) (reproduced from [33]). 1. The growth apex of stolon. 2. Stolon. 3. The top of a growing shoot. 4. Hydranth. 5. Calicle. 6. Offshoot. 7. Gonangium. 8. Hydranths that capture prey. 9. Hydranthsexcretions.

To clarify some specialized features of the structure and functioning of colonial organisms, nine more species were used besides the above two:

Clava multicornis (Forskal, 1775) (Clavidae);
Ectopleura larynx (Ellis et Solander, 1786) (Tubulariidae);
Abietinaria abietina (Linnaeus, 1758) (Sertulariidae);
Hydrallmania falcata (Linnaeus, 1758) (Sertulariidae);
Sertularella gigantea (Mereschkowsky, 1878) (Sertulariidae);
Sertularia mirabilis (Verrill, 1873) (Sertulariidae);
Laomedea flexuosa (Hincks, 1861) (Campanulariidae);
Obelia geniculata (Linnaeus, 1758) (Campanulariidae);
Obelia longissima (Pallas, 1766) (Campanulariidae).

Experimental techniques have been described in earlier publications [20, 23, 26, 27, 29-31, 40-43].

The branched tubular body of a colonial hydroid is formed by the *stolon*, which adjusts to a substrate, and by *hydranths*, which branch from the stolon, or *shoots*, which bear hydranths (Fig. 1).

Body wall is composed of two layers of myoepithelial cells (MEC) with a thin non-cellular mesogloea *(basal membrane*) between them. A two-layered body structure is featured by both, the hydranths and the *coenosarc*, which connect hydranths. In addition to MEC, the outer layer of cells (*epidermis*) comprises several types of specialized cells, including glandular, urticant, nervous and undifferentiated cells (i-cells). The epidermis secretes the chitin-like envelope (*perisark*), which serves for protection and support. The inner layer of cells (*gastrodermis*) contains glandular cells in addition to MEC. The common cavity of the tubular body is filled with a liquid (*hydroplasm*), containing food particles derived from prey partially digested by hydranths. Growth is confined to certain areas of the body, i.e. to the *growth zones*. The growth zones are usually located directly after the terminal sections of the stolon and shoots, which are called *growth apexes*. Branching is of the budding type that is the initiation of new growth apexes is confined to certain areas, i.e. *budding zones* [33].

Analysis of Findings obtained in Studies of Hydroids and Other Colonial Organisms

In the past, a unitary organism was considered as an individual, whereas a modular organism, as a colony of individuals. However, this assumption proved to be erroneous [33]. A colonial organism originates from the zygote or a part of the body of the maternal organism, and all its modules are the parts of the same whole having common metabolism, whereas organisms that coexist in a genuine colony originate from different ancestors and do not constitute a single organism having its own

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metabolism. A unitary and a modular organism are both individuals, but they represent two opposite strategies of morphogenesis: any repetition (multiplication, polymerization) is attenuated according to one of them or is enhanced according to the other. It is believed that the vegetative reproduction represents an intermediate strategy of morphogenesis or, possibly, a transitional stage between the unitary and the modular organization.

Vegetative Reproduction

The vegetative reproduction is widespread in all kingdoms of life, including invertebrates [19]. This mode of reproduction provides for cloning of individuals, increasing of population size rapidly under favorable conditions, and recreating a population from a particular individual. At the same time, the vegetative reproduction often results in overpopulation and increased intraspecific competition [68, 90]. Therefore, the vegetative reproduction is most beneficial under conditions of high mortality and least beneficial under stable conditions characterized by low mortality [33].

The transition from the vegetative reproduction of unitary individuals to the modular organization of decentralized organisms is theoretically possible in cases where, for some reasons, the daughter individuals do not separate from the maternal one. As early as in 1744, Abraham Trembley described a hydra, in which offspring separation occurred with a delay sufficient to allow budding and the appearance of second-order offspring on buds (Fig. 2) (see [56]).

This phenomenon was studied in more detail in *Moerisia maeotica* ("marine hydrae") in which the delayed separation of daughter zooids develop upon food deficiency [27]. The daughter species that remain connected with the maternal organism can get food from a temporary colony (Fig. 3).

According to G. Spencer [55], a delayed separation of individuals during vegetative reproduction may be fixed in evolution if it is beneficial in some way. This eventually may result in temporary to permanent colony transformation. This assertion seems so logical that it has never been checked. There was a theory of gradual strengthening of individuality of a colony associated with decreasing the individuality of individuals therein [1]. However, closer examination of various examples revealed internal contradictions in this concept [33]. Some large taxa, such as the type Bryozoa and the subclass Octocorallia were found to have no primary single organisms. Instead, colonial and secondary single individual organisms developed only upon the reduction of coloniality [1].

The hypothesis that coloniality results from vegetative reproduction is inconsistent from the morphogenetic point

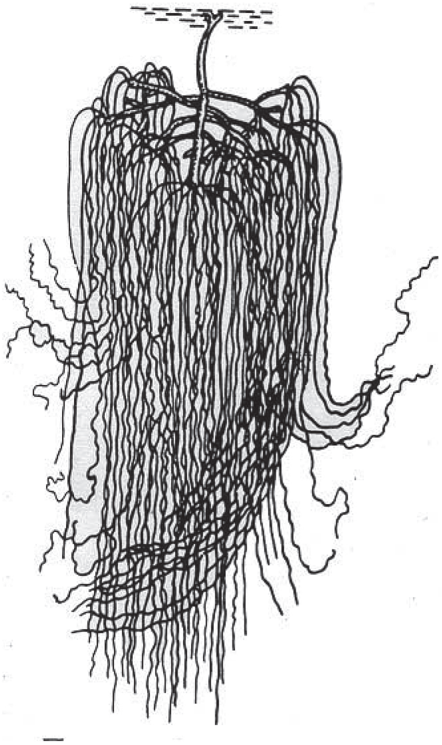

Fig. 2. Temporary colony of hydras developed as a result of delayed separation of the daughter organisms from the maternal one (see [56])

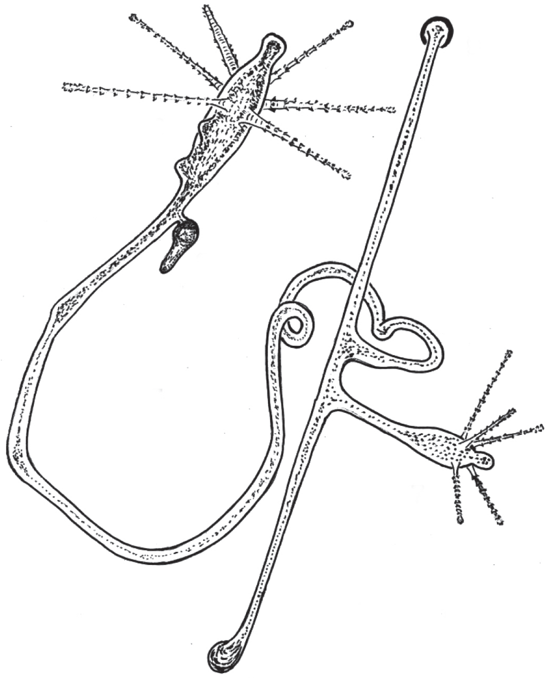

Fig. 3. Temporary colony of *Moerisia maeotica* ("marine hydrae") developed under food deficiency conditions (see [27])

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of view too. Vegetative reproduction can be subdivided into three types based on the localization of the sites of the formation and separation of daughter individuals: 1) transverse division of the maternal body; 2) longitudinal division of the maternal body; and 3) lateral budding from the maternal body (Fig. 4).

If coloniality was preceded by separation of daughter zooids from the maternal body, it is reasonable to expect that a delay of this process would result in the formation of colonies of zooids separating directly from other zooids (Fig. 4, *1*). Indeed, in primitive six-ray corals, colonies develop by the longitudinal division of corallites so that two daughter zooids extend the maternal one to from a bifurcation (Fig. 4, *2*). However, this is not the case in Octocorallia and Hydrozoa. Their zooids are connected to each other indirectly via the coenosarc, i.e., the common body of the colony. In Octocorallia, zooids are formed from the collenchyma (Fig. 4, *4*); in hydroids, they are formed from the stolon (Fig. 4, *3*) [33].

In the case of, e.g., hydroids, it is reasonable to assume that at first there could be a single ancestor, then a polyp with a stolon, and thereafter a colony. In this sequence of events, the vegetative reproduction occurs at the final stage: the formation of the daughter individuals take place not on the maternal individual, but on new structures not featured by unitary individuals, i.e., the coenosark and the stolon. The mode of initiation and arrangement of zooids in the simplest colonies of hydroids suggests the leading role of the proliferation of the basal part of polyp body without the direct budding and separation of the daughter polyps.

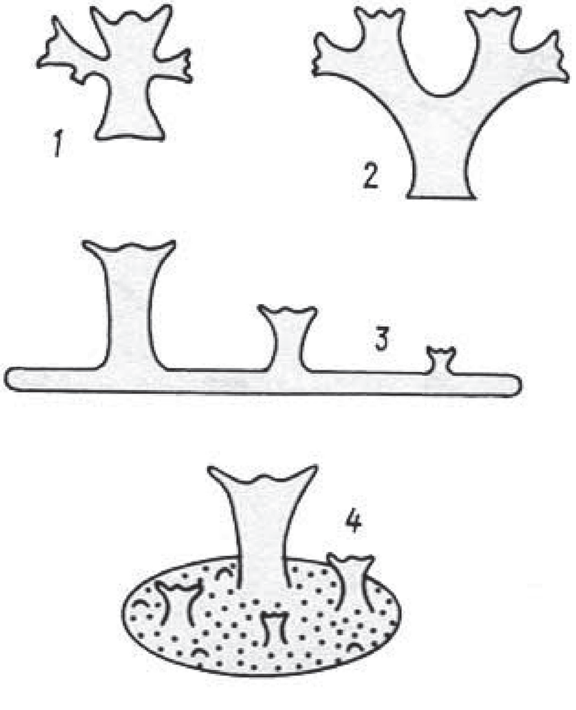

Fig. 4. Variants of zooids positions relative to each other during colony formation: 1) upon lateral division; 2) upon longitudinal division; 3) upon budding from the stolon; and 4) upon budding from the collenchyma (reproduced from [33])

If zooids of the colonial hydroids are formed on the common body rather than on other zooids, then coloniality could not result from the vegetative reproduction of non-colonial ancestors, which did not yet have a common body, and thus their budding or division occurred directly on their zooid. This contradiction casts doubts on the hypothesis that coloniality evolved via vegetative reproduction.

The above contradiction may be resolved upon the assumption that the unitary organization, vegetative reproduction and modular organization are the three components of the same phenomenon, which are expressed differentially depending on the morphogenetic capabilities of a taxon and the ecological strategy. This phenomenon is polymerization. The absence, or rather the blocking of polymerization, is a prerequisite of the unitary organization. Polymerization associated with the formation of detachable units is vegetative reproduction. Polymerization associated with preserved connections between the units formed is a way to increase the size of a body. Each of the three variants of the polymerization process has its own specific morphogenetic and ecological features.

Polymerization as the Basis for the Formation of a Modular Organism

Polymerization and oligomerization are two opposite mechanisms for changing the organization of any system [12]. Polymerization is multiple repetition of a certain structure [16]. The emergence of multicellular organisms also fits the concept of polymerization [17]. Daughter cells, which remain being connected with both the maternal cell and other daughter cells, become not just a community of cells, but rather an integral structure of a higher level than that of an individual cell [18, 62]. Polymerization can also take place in a multicellular organism in the form of repetitions of certain parts of its body or organs [14, 15, 57]. Multiple repetitions of the same structures result in the development of metameric animals (polychaetes, arthropods) and all modular organisms, no matter what type they belong to [39].

Oligomerization is a reduction in the number of repeated structures, i.e., cells, segments, organs, or zooids. Oligomerization occurs in parallel with increasing the centralization and integrity of abody.

Oligomerization is one of the mechanisms of the evolutionary complexification of organisms. There are many examples of the initial multiplication of an organ, e.g., the limb in arthropods, followed by the specialization of the emerged repeats and reduction in their number in the course of subsequent evolution [13]. Biological evolution as such is a consequence of increasing the number and diversity of features, individuals and populations, and of subsequent natural selection and specialization.

Polymerization and oligomerization take place not only in nature, but also in society. Polymerization may be exemplified with the increasing number of workers employed in some production as well as with the growth of network institutions, the construction of unified multi-apartment houses, and the expansion of urban areas. Oligomerization may be illustrated with the reduction in the number of employees due to the specialization and increased productivity of the remaining staff, with complex shopping centers instead of numerous small identical shops, and with increasing the diversity of services and entertainments instead of their multiplication by replication.

In management, polymerization is the predominance of quantity, whereas oligomerization is a qualitative innovation, i.e., improvement.

Polymerization at the level of multicellular organisms is most clearly seen in two the variants of individual structure, i.e., metameric and modular. They are often unreasonably considered sub-variants of the modular organization.

The *metameric* structure of an animal organism is expressed as multiple linearly arranged segments, which are the stereotype parts of the body. In the simplest case, they all are identical, except for two segments, the head and the tail, which differ from the other segments. This makes the metameric structures different from the modular ones. As a rule, metameric animals, such as annelids and arthropods, are unitary and mobile. Metamerism facilitates nervous system centralization and the subsequent segments specialization (oligomerization). For plants, "metameric" is essentially the term used to designate their modular organization [48, 58, 60]. This parallelism stems from the fact that the term "metameric structure" was introduced in botany earlier than the term "modular structure". This resulted in a superficial analogy between body parts repetition in a non-centralized plant organism and segments repetition in a unitary animal organism featuring all attributes of centralization.

The *modular* structure of an organism is expressed in the multiplication of absolutely all of the parts of its body, without exceptions [36, 39]. Modules can be found in colonial hydroids: zooids, segments (internodes) of a shoot, segments of the stolon, shoots themselves, branch shoots, and growth apexes. As a rule, the modular structure is accompanied by branching, i.e., the linearity of such structures is not typical for them.

Whereas the metameric structure is in animals an example of the polymerization of body parts upon preservation of the centralized organization of an organism, the modular organization is an example of the polymerization of body parts upon the loss of the centralized organization of an organism [39]. Therefore, *metamerism is only a variant of the structure of a unitary organism, whereas coloniality, such as of a modular organism, is a variant of an alternative to the unitary organization*. The difference is rooted in the different ways of adaptation to the environment (see below).

Cyclic Morphogenesis as the Basis of Modular Organization

Cyclic morphogenesis is the basis of the formation of a modular organism. Shoots and stolon segments are formed by a certain sequence of morphogenetic changes, which ends to form starting points for the next segments [36, 44]. With regard to plants, this phenomenon is called the "open growth" [25, 48, 59].

Fig. 5 shows the formation of a next segment in a shoot of the colonial hydroid *Gonothyraea loveni*. First, a segment having several identical constrictions is formed on the tube of a shoot, then a smooth segment is formed, then a segment with constrictions is formed again, its beading, however, being narrowed, then a dilation is formed, and finally a zooid emerges and growth discontinues. Simultaneously, a swelling, which is the germ of the next segment of the shoot, appears in a strictly defined place on the boundary between a smooth and a beadlike segment.

Repeated stereotyped segments of a shoot and the stolon of a hydroid are called *interstices*, by analogy with plants [47]. In morphological terms, an interstice is a segment between consecutive branching sites; however, in essence it is the product of cyclic morphogenesis, multiple repetitions of the same growth algorithm resulting in the formation of stereotyped modules of a colonial organism or a plant.

The cyclic morphogenesis is characteristic of modular organisms [39, 48]. Instead of growing in size and becoming progressively differentiated, as it is inherent in unitary organisms, the modular ones grow predominantly outside the formed parts of their bodies (their modules). The next growth zone is laid, the next segment of the body is formed, and a new zooid develops. The cyclic morphogenesis in hydroids and bryozoans is usually brought about by branching of the longitudinal chains of modules, such as the longitudinal division of an acrescent corallite of a coral.

As a variant, cyclic morphogenesis may be realized as a permanently functioning growth zone, on which the rudiments of hydranths or shoots are regularly formed (Fig. 5). That is how the stolon in hydroids, complex shoots [32] and marginal growth zones in some corals, the apical growth zone in *Acroporacorals* [28], and the growth apexes in highly organized hydroids, e.g., *Dynamenagenus* [34], function.

Once started, a morphogenetic cycle usually continues even under unfavorable conditions, as for example in the case of food deficiency, until the completion of an internode or zooid formation, after which growth may stop until the conditions become favorable again. Therefore, the number of growth zones in a modular organism can be not only increasing, but also decreasing in accordance with the amount of food received [2-5, 41]. Thus, *cyclic morphogenesis turns out to be a part of feedback in self-regulation of modular organism growth, so that a change in the number of growth zones is proportional to the amount of food received.*

Proportionality in the Modular Organisms

Almost all unitary organisms have definite body shapes, which maybe expressed as the ratios of the lengths and widths of their body segments, limbs, organs, etc. Certain proportions of the linear dimensions or volumes are characteristic for each stage of life cycle and may be expressed as indices. In the process of growth, proportional relationships between body parts may be constant (the isometric growth) or may change (the allometric growth). In any case, the proportionality of body-build is an indispensable characteristic of unitary organisms.

In modular organisms, the concept of proportionality of the body shape is applicable to its separate parts, for example, to zooids, leaves or modules. However, the shape of a modular organism, especially a branched one, is so variable and unstable that for long no attempts have been being made to find proportions in the colonies of hydroids, corals or bryozoans. It was believed that any colony, being an association of individuals, is not subject to restrictions applicable to organisms.

Nevertheless, the morphological integrity of colonies has been found, at least in hydroids [23, 26, 33]. The proportionality of a colonial organism is expressed as the ratios of its modules: the number of hydranths vs. the number of growth apexes (H/T); the number of hydrants vs. the length of the cenosarcum of the entire colony (H/L); and the number of growth apexes vs. the length of the cenosarcum (T/L). The ratios between the numbers of colony modules are maintained within certain limits during colony growth. This is an indirect confirmation of a feedback between the number of zooids and the number of growth apexes, as well as the rate of growth.

Such feedback is realized through cyclic morphogenesis. When food is in excess, branching of shoots and stolon takes place, i.e. there appear additional growth zones that consume the available cellular material. Upon food shortage, some of growth apexes cease functioning at the stage of morphogenetic cycle completion. As a result, cell material necessary for growth is reallocated to the remaining growth apexes and, primarily, the stolon. This means that *the structural proportionality of a colonial organism is realized through changes in the number of different types of modules in it* [40].

Limitations to the Morphogenesis of the Parts of a Modular Organism

Even though the shape of a modular organism varies widely, the shape of its individual parts may be quite stable,

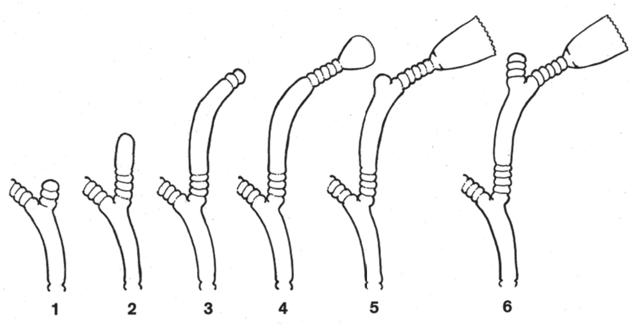

Fig. 5. Cyclic morphogenesis of a shoot in the colonial hydroid *Gonothyraea loveni* is an example of a temporarily functioning growth apex (see [33]): 1 to 6: the successive stages of shoot growth (the formation of a module)

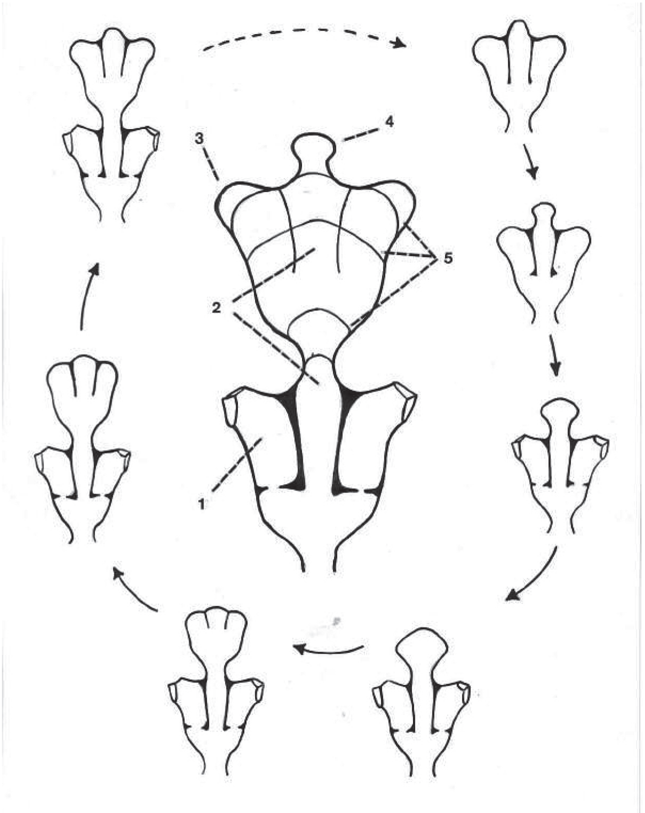

Fig. 6. Cyclic morphogenesis of a shoot of the colonial hydroid *Dynamena pumila* is an example of the constantly functioning growth apex (see [34]): 1) hydrotheca; 2) shoot stem; 3) the rudiment of a nascent hydranth at shoot tip; 4) shoot tip; 5) contours of successive stages of shoot tip growth

i.e. comparable to that of a unitary organism. This applies to both, individual modules and supra-modular levels of organization, e.g., to the shape of a shoot and of its branches. There exist feather-shaped shoots, in which the lateral branches are located in the same plane and in a certain order. Shoot morphogenesis in such cases includes lateral shoots initiation in the course of an intermodal development cycle (Fig. 7). This is a more complex variant of morphogenesis, which differs from a simpler one by considerable constraints on budding (lateral buds initiation). In the case of the unlimited growth of lateral branches, shoot shape is not just feather-like but triangular. If the growth of the lateral branches is constrained by a certain number of morphogenetic cycles, then the shape of the shoot is more feather-like, since all of the lateral branches that extend from the shoot stem are of the same length, except for the youngest ones. In all cases, instead of the free initiation of lateral shoots or the unlimited growth of branches and zooids, morphogenesis becomes increasingly constrained as to the patterns or durations of processes implicated in it [23, 32, 104, 111].

The Ecological Importance of the Colonial Organization

The modular structure of an organism is an adaptation to its sessile mode of life associated with that it has to obtain vital resources from the environment that is moving relative to its position.

In animals, the modular organization is always associated with increasing the number of organs for grasping food: “poly-mouthness” or “multi-headedness”. Poly-mouthness, i.e., an increase in the number of zooids, allows a sessile organism to capture food particles or prey suspended in moving water. Poly-mouthness[4] corresponds to the ecological strategy of filtration, i.e., capturing of nutrient objects from water flow, as opposed to the search and hunting strategies. This is true for all colonial invertebrates featuring a common body (cormus), such as sponges, hydroids, corals, siphonophores, bryozoans, and colonial ascidians. The effectiveness of poly-mouthness increases due to specialization in capturing of small prey, its concentration in the environment being much higher than that of large prey. This is easily seen in the evolution of the colonial organization within a class, i.e., from primitive colonies with large zooids to complexly organized colonies with small zooids [32, 47]. The progressive decrease in the size of hydranths is a manifestation of miniaturization, which is a widespread phenomenon in wildlife [54, 71, 132].

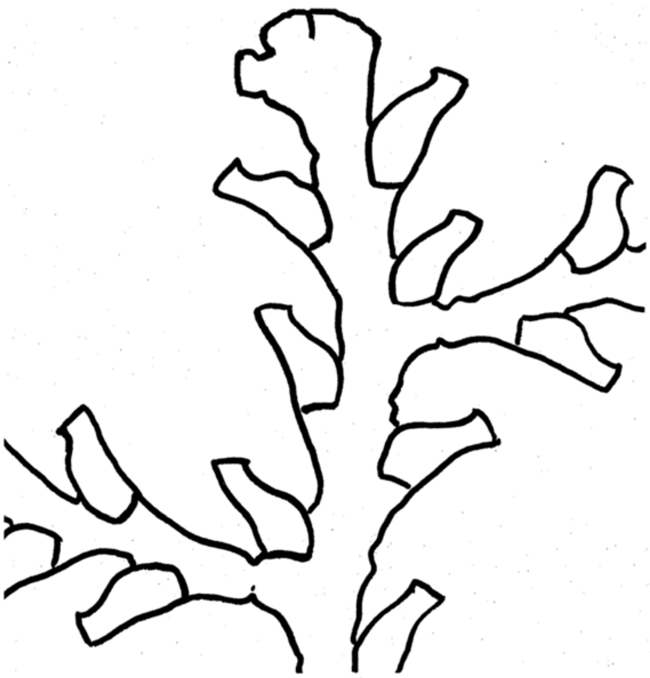

Fig. 7. A feather-shaped shoot of the hydroid *Abietinaria abietina*with a lateral shootinitiated at its growth apex

Miniaturization

In colonial hydroids, miniaturization as an evolutionary trend is manifested in the order Leptothecata, which differs from the order Anthoathecata by smaller zooids and the presence of the perisark not only around the coenosark but also around the zooids. Because the shape of the perisark around the zooid is significant in taxonomic terms, this structure is termed specifically as “hydrotheka”. At difference from all Leptothecata hydranths, which stop growing after the completion of their morphogenesis, Anthoathecata zooids continue to grow after their morphogenesis is completed, i.e., after tentacles and oral opening have developed and independent capturing of food has become possible. Underdeveloped hydrants are able to capture prey, hold it with tentacles, swallow and partially digest it. However, they do not form the reproductive organs, gonophores, where the baby medusas with sex gonads or the gonads themselves develop. Growth cessation in zooids is associated with blocking of cell proliferation within their bodies [40].

The above affects not only the growth of zooids, but also the duration of their life cycle, because the insufficient replenishment of cells results in the depletion of the originally available reserves of the most readily spent cells, i.e., urticant and glandular cells. That is why hydranth lifespans known from the literature are shorter in the order Leptothecata than in Anthoathecata [27, 29, 30, 42, 80].

Filter Feeding

Filtration of small particles from water is a mode of feeding common to both, unitary and modular aquatic

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[4] Environmental strategy [150] is a convenient and capacious concept not limited to nutrition, behavior, reproduction or life forms. For example, the evolutionary adaptation of hydroids to feed on small prey is accounted for by at least three specializations: attachment to the substrate, a branched body shape, and a small size of zooids (miniaturization).

invertebrates [83]. The specific feature of adaptation of modular invertebrates to capturing of water-borne food particles is their attachment to the substrate and formation of a kind of net by their branched body. Within the class Hydrozoa, this environmental strategy is clearly expressed in the orders Anthoathecata and Leptothecata. Other modular animals not referred to the class Hydrozoa are also specialized in consuming small food particles from the surrounding water mass [82, 106, 136]. Only the most primitive representatives of modular organisms, such as some corals that have large and innumerous corallites, are able to feed on large prey [158].

Hydroids and corals capture food objects with their specialized harpoon cells, cnidocytes. Bryozoans and camptozoans filter out small particles with cilia on tentacles located outside of zooid body. Sponges and ascidians also filter water with cilia, but by passing it through the cavities of their bodies.

The transition from the unitary to the modular organization ensures the formation of a networked body without significant rearrangements of the primary structure.

With increasing the number of organs for food capturing, the success of each individual attempt to retain prey becomes less significant, whereas *the size of the "net" and the way of its optimal spatial organization become the main factors of successful feeding.* Therefore, of paramount importance are the order of body branching and the distance between zooids.

This trend is clearly seen in every group of modular animals. In hydroids and eight-ray corals (Octocorallia), the most perfect are the feather-like shoots that are oriented across the prevailing water current [87, 105, 133, 151, 156]. The formation of such a structure is accompanied by ordering of its branching and restricting of the growth of zooids and higher-order branches [43, 103]. The effectiveness of filtration [45] and, therefore, of growth and reproduction depends on the ability to withstand the flow of water. A number of features of shoot morphology determine the ability to withstand bending, i.e. the ability to stay across the flow of water [108]. The shoots of hydroids become stronger when shoot stem diameter and walls thickness increase, several trunks are fused (polysiphonism), the inclination angles of hydranth axes relative to trunk axis are decreased, the calycles are fused with the trunk, hydranth and calycle size is decreased to the extent that calycles become constrained inside the trunk, etc.

Modular organisms of plants have a similar arrangement. Leaves are analogous to zooids. The size of the leaves and their optimal distribution in space are important for capturing sunlight. In the evolution of the modular organization of plants, the importance of the optimal arrangement of light-capturing leaves rather than of their size increased.

Ingrowth into the environment

Sessile organisms usually dwell in a complexly organized space among other organisms, both modular and unitary. Being unable to change their position by movements and other behaviors, modular organisms, nevertheless, can perfectly conform to the spatial heterogeneity of their environment [93]. The simplest form of ingrowth into the habitat is manifested as the dependency of the form of a colony on the form of its limiting substrate. Thus, the stolon of the hydroid *Orthopyxis crenata* grows mostly longitudinally [6] on the long and narrow leaves of the alga *Phyllospadix iwatensis.*

The shape of a coral colony often depends on the environmental anisotropy, which manifests itself, e.g., in uneven illumination or horizontally stratified water flow [77, 120, 155]. In densely packed communities of corals, any colony turns out to conform exactly to the intricate shape of free space between the neighboring colonies. Coral branch growth stops when adjacent sessile organisms are approached. Stinging cells shoot at dangerously approaching objects. Such combats and their consequences are amply described in the literature [135]. The same maybe seen in the case of plants [72, 127, 147]. Fir trees that grow on open space are symmetric, whereas those that grow in a forest close to other trees are asymmetric. Such asymmetry of an individual tree is determined by the proximity of the neighboring trees on its one side and of free space on its other side.

The shapes of all modular organisms are very diverse, vary in the course of their development and correspond to the area occupied by them in the environment. In plants, the growth of branches is inhibited in the shade, including the shade of a neighboring plant crown [127]. At the same time, branches grow faster on the illuminated side. In the case of hydroids, the growth of the pivot of a colony, i.e. its stolon, and of the outgoing side stolons and shoots depends on the amount of food received by zooids in a particular part of the colony [3]. Growth in the direction where food is most limited slows down or discontinuer. Growth in the direction where food is ample is accelerated, additional shoots are formed there, and lateral branches of the stolon, shoots on them, and lateral branches of the shoots develop. A colony sort of "grows into the available space" and, as a result, closely conforms to it spatially due to branching. The planes of feather-like shoots of hydroids (Abietinaria, Sertularia, etc.) and eight-ray corals (e.g., Gorgonaria) always stand across the predominant direction of water flow [133].

Modular organism "ingrowth" into the surrounding anisotropic space is based not only on a certain degree of independence of processes in the different parts of an organism, but also on the mandatory general organismal integrity. The integrity manifests itself, first, in allocating food resources to those parts of an organism that cannot feed themselves, primarily to the growth zones, and,

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Marfenin N.N. Decentralized organism exemplified with colonial hydroid species.
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second, in the termination of growth zones functioning in the inefficient body parts and in the orderly resorption of zooids and coenosarc where food is chronically deficient, followed by digesting the cells of these zooids and by transporting the nutrients thus released to the other parts of the colonial organism [5].

Overcoming of Age Restrictions

Changes in the shape of a colonial organism are facilitated by not only the uneven growth of its various parts, but also by the short "lifespan" of zooids. The duration of functioning of food-producing zooids in the hydroids of the order Leptothecata, e.g. in a *Gonothyraea loveni* colony, ranges from two to nine days, whereas the colonial organism itself lives for more than a year [42]. Zooids in hydroids referred to this order grow old and dissolve due to depletion of some cells [80, 40] that are spent in the course prey catching (cnidocytes) or digesting (gastrodermal cells). This is the price for miniaturization and specialization in feeding on small prey.

The cells that make up a zooid do not just disappear for nothing by the end of its life cycle. Instead, they become digested, i.e., absorbed by their colonial organism not only where an aged hydranth dissolves, but by other parts of the body too. During resorption, a zooid undergoes successive stages of dedifferentiation, similar to the reverse development, i.e., tentacles become shorter and then disappear, and the body of the zooid rounds up and shrinks [98]. At the same time, cells from zooid walls enter the gastrovascular cavity where they disintegrate, and their fragments are transported by hydroplasm to other parts of the colony [73].

If there is enough food in the colony, new zooids form within 24 hours at the site of the dissolved zooids, but this does not happen if food is scarce [33]. Upon a more severe starvation, the oldest part of the colony body, its coenosarc, undergoes resorption [3, 5]. Thus, the form of the colony changes not only due to its growth, but also due to involution depending on the availability of food. Old zooids and shoots resorption associated with the continuing growth of stolons slows down colony movement on its substrate.

Repeated events of zooids formation or coenosarc restoration is an amazing example of rejuvenation of an organism [42]. Young zooids replace the resolved ones thus making it possible to overcome age limitations.

Body decentralization is the main prerequisite for significant changes in body shape, as well as for rejuvenation of the components of a colonial organism.

The Size of a Modular Organism

The size of a modular organism, i.e. the number of its zooids and the extent of their control over the surrounding space, determines the prosperity of the respective species. Whereas in the unitary organisms their body weight and strength and the size of their mouthpiece determine the maximum size of their prey, in the modular organisms their body size primarily determines the size of the "trapping network", which is a set of small trapping organs distributed in space.

Since the bulk of food captured by individual zooids is consumed not by those zooids that have acquired it, but, instead, is assimilated by the other parts of the colonial organism [24], the growth, branching, and eventually the rate of further increase in the colonial organism depend directly on the number of zooids.

Theoretically, there are no limits to body size and age in the modular organisms. The most striking findings to illustrate this assertion have been obtained in studies of the aspen-poplar (*Populus tremuloides*), which produces shoots from a system of branched rhizomes. The estimated weight of this huge branched organism, which has been growing for more than 80,000 years over a large area in the Fishlake forest (the USA), is about 6,000 tons [118].

Colonial animals, so as trees, could grow indefinitely, if not for external circumstances. Many hydroids die under layers of precipitates or of sediments formed by new organisms or die after the death of the algal substrate on which they grow. Corals can reach enormous ages, up to hundreds and even thousands years [129, 137], but most of them live in an overcrowded space where continuous growth is impossible. Corals may also die because of the impacts of intense waves able to break calciferous colonies or because of fouling organisms or environmental changes, e.g. in temperature regimens. Modular organisms usually do not die of old age; however, simultaneously with their body growth, there may take place their spontaneous auto-fragmentation into parts that continue to grow further [95]. Auto-fragmentation makes it possible to avoid excessive concentration of zooids in the space occupied by them and at the same time to continue their vegetative proliferation.

The larger a colony of hydroids is, the longer it is able to withstand starvation. The physiological integration of the colony provides for the use of the available cellular material for nutrition under nutrient deficiency. Whereas unitary organisms have certain tolerable emaciation limits, beyond which their organs lose the ability to perform their functions, a modular organism, by contrast, reduces the size of its body by decreasing the number of identical modules [34, 80]. In doing so, the organism remains viable and can recover even from a single zooid or a fragment of its coenosarc. The simplicity of organization and multiplication of all vital organs of colonial organisms is what ensures their high viability.

The larger a colony, the more prolific it is. The number of reproductive units produced (medusas, planulas, or frustules) depends on the size of the colonial organism and can vary within very wide limits. There are many examples of high fertility of unitary organisms. The number of germ cells in one unitary individual may amount to thousands.

However, this does not mean that the fertility of a unitary organism can increase thousand times in a favorable year. The fertility of a population of unitary organisms depends on not only living conditions, including the abundance and availability of food, but, also, on the size of the fertile population, which is determined by the previous breeding cycles and habitat conditions. No matter how optimal conditions for reproduction develop in a given year, the number of breeding individuals usually increases only slightly (mainly due to reduction in their mortality).

In this regard, the modular organisms are different, especially those that feature a high growth rate. Under favorable conditions, a modular organism increases in size many times before it begins reproduction. Thus, the modular arrangement is better adapted to rapid changes in body size and makes it possible to use favorable growth and propagation seasons more efficiently than it is possible for the unitary organisms. There is still no direct evidence in favor of this assertion, but simple calculations show that the growth and fecundity of fast-growing modular organisms are much more variable than of the unitary ones. Only the unitary organisms that are capable of vegetative reproduction can respond to growth of food resources as effectively as the modular ones can [10].

The growth rate of a modular organism is determined by the specific features of its configuration. The slowest growth rate is featured by massive colonies and the fastest growth rate, by branched colonies that feature thin branches. This has been shown in corals [75, 79]. Branched colonies attributed the genus *Acropora*can grow at a rate of 5 to 20 cm per year, while massive colonies, for example referred to the genus *Montastrea*, at a rate of only 1 to 5 mm per year.

In many colonial hydroids, the daily growth rate of individual branches reaches 1 to 2 mm or more [41, 160]. It is meaningless to calculate their growth per year, since the time of branches and shoots growth is limited, and the increase in the length of the entire branched body of a colonial hydroid depends on its branching. Nevertheless, it seems worthwhile to cite the following data to compare colonial hydroids and corals: the length of one stolon of *Gonothyraea loveni* or *Obelia longissima* colony increases by 5 to 10 cm per month upon moderate uninterrupted feeding at a temperature of 14 to 16 °C.

Such high growth rate is accounted for by the fact that stolons and shoots bodies in the colonial hydroids are tubular, that is almost cylindrical, and the thin walls of the tubes consist of only two layers of small cells separated by the basal membrane. Wall thickness of such tubular body is only 20 to 30 m. It is known that generally the surface of a unitary organism increases twofold when its volume increases three fold [61]. In colonial hydroids, both the surface and the volume of their bodies correspond exactly to their linear dimensions, so by measuring the length of stolons and shoots one can estimate the weight of the colony by multiplying its total body length by a certain constant obtained empirically or by calculations. Upon some allowances, this statement is also true for all other types of modular organisms: fungi, plants, other colonial invertebrates [8, 112]. Thus, the modular structure provides for not only variation of body size within a wide range, but also for rapid grow under permissive environmental conditions.

Motility of the Modular Organisms

The vast majority of the modular organisms are sessile, except for syphonophores (the order Syphonophorae of the class Hydrozoa), salps and pyrosomes (the class Thaliacea of the subtype Tunicata), which slowly sail in water mass due to pulsations of their bell-shaped modules or whole bodies. This is sufficient for syphonophores to trap their prey better and for salps and pyrosomes to filter phytoplankton better. Other sessile modular organisms cannot travel in space by moving their bodies. However, they can travel from one place to another due to the growth of their stolons, which enables them to settle down at new places at the expense of leaving their died out old parts behind.

Such subtle and slow displacement along the substrate can actually lead to significant changes in the conditions of existence. Many colonial hydroids grow on algae. For example, *D. pumila*, *G. loveni*, and *L. flexuosa* live on rockweed thallomes. Dwelling conditions and especially nutrition often differ significantly on the opposite planes of the same thallome. On the inner plane, which faces the neighboring rockweeds, the probability of contact with a prey is much lower than on the opposite plane, where water flow in algae thickets is decreased.

Rockweed thallome width does not usually exceed 2 to 3 cm. As a colonial hydroid grows, its stolons reach the edges of its substrate (in this case, rockweed thallome) and pass to its opposite side. If hunting conditions are better on that side, the rates of stolon and shoots growth and branching increase, thus increasing the number of zooids and the amount of food received by the colonial organism.

Discussion: extrapolation of conclusions

Studying the decentralized organization as it is exemplified by the colonial hydroids allows presenting this phenomenon in its “pure form”, that is, in the absence of the hierarchically ordered regulation of the vital activity of an organism and, at the same time, upon multiple duplications of all processes in it. The parallelisms of processes and their essential independence from each other distinguish fundamentally the decentralized organization from the centralized one. In addition, a system featuring the decentralized self-regulation is easily represented as a set of certain processes and simple measurable indicators.

As shown above, the decentralized organization of the colonial hydroids may be characterized with the following general features:

– *Multiplication* (*or*, according to Zamorsky, *polymerization* [15]) within the limits of a multicellular organism, which is usually regarded as incomplete vegetative reproduction;

– *The absence of regulatory organs*, which are characteristic of the unitary multicellular animals;

– A *considerable independence of components,* i.e. modules and their aggregates (shoots, colony rays), which is expressed in their independent behavior, growth, and morphogenesis;

– A *high resistance* of a colonial organism to impacts on its individual parts;

– The *plasticity of the shapes* and a wide variability of the sizes of adult organisms;

– *"Ingrowing" into the surrounding space, that is* the conformance of the shape of a colonial organism to the surrounding space, which may be anisotropic with regard to the distribution of environmental factors;

– *A network body shape* adapted to capture food and to be fixed on places suitable for life;

– *Cyclic morphogenesis*, i.e. a repetitive algorithm of the formation of the modules of a colonial organism;

– *Overcoming of age restrictions due to* the renewal of modules by their orderly resorption and substitution with new ones.

The above characteristics of decentralization are featured not only by colonial organisms, but also by supra-organismal biological and social systems, i.e. populations, ecosystems, and different social groups.

Multiplication

Whereas a colonial organism is formed by incomplete vegetative proliferation, the *populations* of any species exist due to the completed reproduction of organisms, both sexual and asexual. In both cases, the repeated reproduction of stereotyped components is indispensable for maintaining a complex system. It is not much important how to term this process, i.e. reproduction, multiplication, transcription or polymerization. The result is anyway a set of similar elements, which are equivalent and therefore are not co-subordinated hierarchically in terms of their interactions. An individual is the module of a population. A cenopopulation of different species and their groups is the module of an ecosystem. Humans and their groups are the modules of a social system.

As the components of a system undergo differentiation, i.e., as their diversity increases and their functions become divided between them [13, 50], and as the number and varieties of interactions grow, the degree of integration of the whole, which consists of numerous elements (modules), increases. Integration manifests itself in the ordering of structure (morphological integration) and in the enhancement of self-regulation processes (functional integration).

A colony of independent individuals, such as bees or ants, is a specialized variant of a part of a population where relationships between the members of a family are structured, and individuals are specialized in their specific functions or even are different morphologically (polymorphism).

A society is a particular case of population featured by the species *Homo sapiens*. A diversity of variants of centralization is possible within it, and multiplication manifests itself not only in population size, but also in the sizes of the groups comprising the population.

Within the multiplication context, an ecosystem is the community of species. This approach makes it possible to consider integration processes not only between separate individuals, but also between the cenopopulations of different species making up a biogenocenosis. The number of species is determined by the specifics of the habitat and by the duration of the stable existence of an ecosystem [130, 161]. Interaction between species in an ecosystem is generally represented by mutually complementary trophic levels, i.e. producers, consumers and decomposers, which provide for the turnover of substances, that is, for the renewal of resources.

Essential Independence of Components, i.e. Modules and Their Assemblages

This is a distinguishing feature of all non-centralized systems. At the same time, connectivity between the parts and the whole is still quite evident in animal colonies, in populations, and in ecosystems. Population density is important for every member of a population. On the other hand, the condition of each individual can affect the entire population, e.g. in the case of the spread of infectious diseases. At the ecosystem level, the stability of the entire ecosystem is an important factor for each of the species in it. The stability of an ecosystem depends on its size and on the degree of species duplication at its trophic levels [63, 100, 101, 114, 115]. This also reflects the reciprocal dependence of an ecosystem upon its species. Hence, non-centralized systems are characterized by both the essentialin dependence of their components and their high integrity. The latter is different from the integrity of an organism, yet is still indispensable for invertebrate colonies, for populations, and for ecosystems.

The Absence of Regulatory Structures

All non-centralized systems exist without control structures. Nevertheless, they are characterized by varying degrees of integrity. The highest integrity is featured by organisms. Even a decentralized organism is not disunited but is an integral body. Each individual parts of such an organism is connected with its other parts by receiving food or nutrients from them and by at their disposal completely; that is, for example, zooids of colonial hydroids may decrease in size (resolve) locally because of a number

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of causes making their cell mass to compensate for the lack of food in the other locations of a colony.

Colonial insects also lack control structures, although the activities of an entire anthill or hive community seem to be ordered and coordinated. This is caused by a high interactivity between the members of a colony, which implies that in their activities every member of the colony affect the others in one way or another. With all irregularity and stochasticity of their interactions, instincts inherent in them predetermine the overbalance of the positive results of activities vs. the negative one.

The lack of managing structures is even more characteristic for populations and ecosystems. The combination of the habitat proper and the genetically determined responses to the environmental factors provides for a certain degree of integrity of both the populations and the ecosystems. For example, the existence of a forest biogeocenosis is possible only under certain climatic conditions depending on the relief and soil. Ponds and lakes are possible only in the hollows of a relief. That is how the environment determines the boundaries of an ecosystem. However, the ecosystem itself changes its habitat and makes the conditions that contribute to its self-maintenance. For example, luminance is lower under forest canopy, and this affects meadow plants growth negatively and forest plants growth positively.

High Resistance to Impacts on Individual Parts

This is a typical feature of the non-centralized systems. The higher system integration is, the greater is the effect of every system component on the rest of the system, and, therefore, the stronger are the consequences of an impact on one of the components of the system for the rest of it [102, 126]. Vice versa, the lower system integration is, the weaker are the consequences of an impact on one its component for the rest of them and for the whole system. All non-centralized systems, be it a modular organism, an animal colony, a population, or an ecosystem, easily survive the damage or even the loss of any of their parts [49, 116, 134, 157].

By contrast, the centralized systems are very vulnerable to damage. It is easy to kill a unitary organism and much more difficult to kill a modular organism. High centralization becomes possible in nature because numerous genetically identical organisms are reproduced in a population. The loss of individual organisms is compensated for by the reproduction of other identical organisms. Population is a typical non-centralized system featuring low vulnerability to local impacts.

It is only due to the existence of the non-centralized organization that centralization becomes possible in the individuals reproduced in a population. In other words, high centralization at the organismal level has become possible only due to the non-centralized self-regulation and low integration at the population level.

The very existence of the centralized organization of a system is possible only if there is a well-developed non-centralized system of which the centralized one is a part. Thus, centralized and non-centralized self-regulation are the two sides of the same coin, i.e. one is impossible without the other.

The Plasticity of the Shape and the High Variability of the Dimensions of an Object

These properties are expressed in non-centralized systems much more strongly than in centralized ones, e.g. in unitary organisms. Actually both, the plastic form and the indefinite size, are important advantages of the non-centralized systems compared with the centralized ones. Any population can provide for the preservation of its species, regardless of the shape and size of the population, if death rate does not exceed birth rate.

"Ingrowth" into the Surrounding Space

This ability is featured not only by modular organisms, such as colonial invertebrates, plants, and fungi, but also by supra-organismal systems, i.e. populations, ecosystems, and social groups. All of them produce excessive numbers of individuals that settle down "randomly" at all possible locations. Those that found themselves in favorable habitats survive, and the rest die. This "trial and error" method makes it possible to use the available space effectively and to spot places that are difficult to detect even by sophisticated targeted searching. This is analogous to speciation by natural selection, as well as to free (i.e., non-centralized) market economy. At the first glance, "ingrowth into the environment" is accompanied in all cases by significant expenditures in terms of both materials and time. Many individuals die, and many social initiatives are doomed to fail in the course of the non-centralized expansion of a population, ecosystem or market. However, the positive effects cover the costs by allowing a population to accommodate to a new place, and, in the case of a successful company, to a new free market niche to gain more profit. The idea of costs thus proves to be erroneous, since material losses must be proportioned not only to the capacity of a system in the present, but also to its capacity in the future, i.e. as it will develop.

The Network Shape of a Non-Centralized System

In colonial organisms, their non-compacted bodies with varying degrees of branching are usually well adapted to capture prey from water stream. This has been established by using hydroids and corals as examples [45]. In the true colonies of invertebrates, family members control a large area around the nest in order to collect prey and protect the space occupied by them.

In both of the above variants, the net-like harvesting of food benefits the system as a whole. In a colonial organism, food obtained by one zooid is transferred to the other parts

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of the body [20, 29-31, 109, 110, 154]. In bryozoans and ascidians, this occurs despite the absence of a developed distribution system. This is also true of the hymenoptera colonies, where all collected food is available to the whole family and can be used by not only the pickers but by the other individuals as well.

The shapes of populations are also network-like, but the integration effect of this coverage of space is much lower. Populations of all species usually spread over territories rather than concentrate in single places, which obviously corresponds to a network and provides for covering space with such a network. However, populations usually are not characterized by trophic integrations and food redistribution. The main advantage of the network arrangement of a population is the increased probability of getting food, at least by some of its members. This may be enough to save the population itself and thus to preserve the respective species.

For a unitary organism, that is a centralized system, such logic is unacceptable because usually it is not enough for the survival of a unitary organism to provide food to only a part of it since its survival fully depends on the normal functioning of all its parts.

Cyclic Morphogenesis

In general terms, this means a regular succession of developmental states, which ends with the transition to the initial state. According to such generalized understanding, cyclic morphogenesis is not limited to the organismal level alone, but is a particular case of the universal law of cyclicity of natural processes, which is manifested at all systemic levels [21, 64, 69]. As it is known, not only biological processes in bodies, populations and ecosystem, but many physical (e.g. thermodynamics) and chemical processes (e.g. the Belousov-Zhabotinsky reaction) are cyclic too[7]. Social processes also show clear signs of cyclicity, e.g. Kondratyev's cycles in economy [22, 46]. In recent decades, cyclic processes in economics, business, history, politics, psychology, etc. were addressed in many publications.

The succession of generations in a population and wave propagation in an ecosystem are the closest analogues of cyclic morphogenesis among a large number of other analogues [140]. Under the conditions of overt seasonal cyclicity in the environment, reproduction in populations and ecosystems may be possible during certain periods of the year.

However, the cyclic development does not mean that all "modules" of a system undergo developmental stages simultaneously. In a modular organism, the phases of cyclic morphogenesis of its component systems may be shifted. In colonial hydroids, the internodes of shoots and stolons develop independently, whereas bryozoans are characterized by independently developing zooids, and corals, by independent budding of new zooids within growth zones.

In populations, the individual developmental cycles, which usually culminate in reaching the adulthood and in reproduction, also occur independently of each other. In ecosystems, the incoherence of species reproduction may be even more pronounced. However, cyclicity in a habitat common to all may facilitate the synchronization of the processes that are essentially independent from each other.

Cyclicity may be of exogenous or endogenous origin. Exogenous cyclicity depends mainly on external changes. Thus, the seasonal cyclicity is determined by the position of the Earth in its orbit and the location of a given site on the Earth.

The endogenous cyclicity is mainly determined by internal processes in a system. For example, the states of wakefulness and sleep regularly alternate in many organisms, one of the states naturally exhausting itself after some time and making prerequisites for transition to the other state. Such endogenous cyclicity does not change the whole system, i.e. does not drive its development.

In another scenario, endogenous cyclicity is accompanied by certain unidirectional changes in the state of a system after the completion of each regular cycle. An example is the ecological succession, which is a process of unidirectional annual changes in the proportions of species in a biogeocenosis [78, 117, 146][5].

Another example of cyclicity associated with the succession of an ecosystem is its periodic rejuvenation, that is, returning to the initial or an intermediate state of ecosystem development. Being the result of some disturbances of the mature state of the ecosystem because of fires, tempests, or storms, this is usually followed by another cycle of secondary succession [128].

Cyclicity means that development leads to repetition. Only when repetition (multiplication, polymerization) becomes a means for forming multiple stereotyped components of the whole, conditions are created for decentralized reciprocal interactions of equivalent parts. Thus, the endogenous cyclicity of development accompanied by multiplication is the basis of non-centralized self-organization. Such cyclicity is manifested not only in the formation of a colonial organism, but also in cell divisions at the previous level of organization, i.e. in the course of the formation of the multicellular unit organism of a colony, and at the subsequent levels of organization, i.e., at the population and ecosystem levels. The social variants of "cyclic morphogenesis", which have their own specific features, may be considered by analogy with processes at the levels of organisms, populations and ecosystems.

Overcoming Age Limitations

Comparison of unicellular and multicellular organisms offers insights into their age-related features. In unicellular compared with multicellular organisms, lifespans are usually shorter by orders or magnitude (if the existence

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[5] There are various types of successions, but mostly they are driven by internal factors.

of the encysted forms of unicellular organisms is not taken into account). It is difficult to determine the lifespan of individual cells in a multicellular organism. Nevertheless, preliminary data about the lifespans of individual types of human cells suggest that epithelial cells live for 5 days, epidermal cells for 2 weeks, erythrocytes for 150 days, and muscular cells in adults, for 15 years on average [150].

In hydras, all cells are renewed during 20 to 30 days [152], whereas an individual hydra can live for many years [145]. According to our data, the lifespan of a hydranth of the colonial hydroid *Gonothyraea loveni* ranges from two to fourteen days, whereas the entire colonial organism can live for several years [42].

Age limitations in the organismal systems are much more stringent than in the supra-organismal ones. Adaptation to the environment proceeds better at the levels of ecosystems and populations and worse at the level of individual organisms, being limited by their lifespans.

The lifespans of species, which are typical non-centralized systems[6], exceed many times the lifespans of individuals that constitute them. The maximum lifespan of a multicellular animals rarely exceeds 100 years, and in many species is limited to several years [66], whereas the average duration of species existence, according to paleontological data derived from various sources, varies from 10,000 to 5 million years [94, 113, 114, 131]. At the same time, it should be emphasized that at the species level, there is a regular sequence of stages of the historical development of a species, including its formation, youth, primetime, and decrement [90].

At the ecosystem level, adaptation is reflected in varying species composition of a community depending on the conditions of its existence. The tundra, the taiga, the steppe and the desert are vivid examples of responses of respective biotas to their environments, as manifested not only in different species composition, but also in the balanced mutual adjustment of different species to each other, which is expressed in stable turnovers of biogenic substances. Considering ecosystems in their development with due regard to their successions makes it obvious that their lifespans are indeterminate, although they depend on the stability of living conditions.

Populations are able to adapt to the specific features of their habitats due to their genetic variability. The duration of the existence of a population is difficult to define. A success of adaptation of ecosystems and populations to their environments depends not on the duration of their existence, but on the life expectancy of organisms. A shorter life expectancy is associated with a higher probability of rapid adaptation of a species or community to changes in conditions, even though the speed of evolution depends on the duration of life cycle not exclusively, but is determined by a number of other factors [74].

The nodular organisms represent a variant of partial removal of age limitations inherent in unitary organisms, because the modular organization provides for the non-centralized regulation, which provides for a higher stability of a system due to an increase in its morphological and functional plasticity.

Within the above context, age limitations of unitary organisms are necessary because they increase the probability of species survival due to adaptation to environmental conditions.

Combination of the Centralized and Non-centralized Forms of Self-regulation and the Emergence of Centralized Regulation at the Level of the Biosphere

The centralized form of self-regulation has emerged in the course of evolution two times, and, perhaps, the third time is underway nowadays.

Unicellular organisms were the first centralized organisms. The function of a regulatory organ was performed by DNA in them [141, 142]. The emergence of multicellularity was associated with decentralization, i.e. the transformation of the unitary organisms was into the modular ones [18, 123, 124]. The present-time sponges and trichoplaxes prompt an idea about the arrangement and functioning of multicellular organisms without central regulation.

Progressive differentiation of cells [88, 91, 96], body parts and organ systems enhanced the morphological and physiological integration in multicellular organisms, whereas the development of the nervous system was associated with the consolidation and subsequent strengthening of the centralized form of self-regulation [1, 96, 144].

Simultaneously, another decentralization took place at the multicellular level through incomplete vegetative reproduction. As a result, the modular multicellular organisms developed [33]. However, progressing centralization of multicellular organisms remained to be the leading vector of evolution to result in the development of species having a sophisticated brain and higher nervous activity.

Homo sapiens, which is one of such species, has become a monopolist. This species has no competitors, and this has led not only to its prosperity and rapid intellectual development, but also to increasing pressure on the nature. Human race has become a powerful factor affecting the biosphere. Concerns about possible catastrophic consequences of imbalances in the turnover cycles in the biosphere made incentives to revise nature management procedures in the 20th century [37]. However, the imperfection of social processes hampers the practical implementation of the recognized principles and methods

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[6] Species relate to systems with unclear boundaries and insufficiently defined integrity, because there may have been transitional forms between species. Nevertheless, a species is a vivid example of a non-centralized system from the viewpoint of internal relations, i.e. the interaction of individuals.

of rational and sustainable management of nature that provide for the opportunity to maintain the equilibrium of the biosphere long enough (by our standards), despite the anthropogenic impact, which is increasing significantly.

If the Mankind overcomes social contradictions, then, hopefully, *H. sapiens* would be able to manage not only its relationships with nature but also the natural processes themselves, which would mean the consolidation of the potentialities of the initially decentralized self-regulation with the centralized control and with adequate corrections of deviations from the normal biospheric processes. Actually, this is what V.I. Vernadsky believed in when he envisioned the possibility that the biosphere may enter a qualitatively new state, called the ***noosphere*** by him [38].

However, it should be born in mind, no matter how perfect the centralized organization is, that the highest reliability is, nevertheless, ensured by the decentralized self-regulation [9, 85, 86], which thus requires much more attention than it has received so far.

CONCLUSION

Colonial invertebrates are a vivid example of decentralized organization. It is believed that coloniality emerged as a result of the vegetative reproduction, which was not brought to its completion, that is, because many of the daughter individuals remained connected to the maternal one. Plants have a similar structure, except for that their bodies consist not of individuals, but of multiple parts referred to several varieties. Both, colonial invertebrates and multicellular plants, are similar in that they are characterized by the formation of multiple body parts, none of which becomes dominant or controlling. This process, which is universal in nature, is called polymerization. Parts combined to form an integrated whole can undergo specialization and integration. If both of the two processes are not expressed, then such a system (an organism in the present case) remains non-centralized yet integral, because, although all its parts (modules) are equal to each other, their interaction is sufficient to provide for systemic processes. The non-centralized organization has several advantages over the centralized one. Thanks to polymerization, that is multiple duplication, decentralized organisms are resistant to external impacts and easily overcome damage or disintegration into fragments. Under favorable conditions, they can increase their size more quickly and significantly than their unitary “relatives” can. The forms of modular organisms vary widely; and due to that, they can better fit the space occupied by them. The lifespans of modular compared with unitary organisms are less limited because the former undergo constant renewal associated with that younger body parts develop to replace the older ones, which die or dissolve. Such features make modular (non-centralized) organisms well suited for having network-like structures and functioning modes. Colonial hydroids are a convenient model to study and simulate such principles of self-organization, which are featured by other systems, such as populations, ecosystems, social associations of various levels, and ultimately the biosphere at large.

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CYCLIC AND STATIONARY MODES OF THE DEVELOPMENT OF CIVILIZATION IN GLOBAL MODELS

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The World2 model of the global socioeconomic system (GSES) was modified using the Mathcad software environment. Based on the resulting World2-MC model, long-term scenarios of the evolution of GSES were considered, upon the premise that only fuel resources are unrenewable, and were compared with the main conventional global models and the respective algorithms of transition of modeled systems to stable equilibriums. With account for the ecological demography data about convergent oscillations of populations in the course of their transitions to steady states below the maximum population sizes that can be sustained with environmental resources, it has been shown that such convergence may occur if resources for growth have been accumulated before the growth started. This is what is exactly true for fossil fuel resources. The initial level of unrenewable resources is underestimated three- to fourfold in the World2 model. The developmental scenarios realized with the World2-MC model show that increasing the initial levels of resources may lead to oscillations of all components of a modeled system. The numbers of the oscillations range from two to four, and population size in each of the oscillation is limited by not fuel resources but by food deficit and environmental pollution. Each scenario leads to a stationary population size ranging from 1.3 to 1.5 billion. In scenarios accounting for shale oil resources, oscillations number may be as high as 15. Increasing the available power with thermonuclear power production will transform developmental trajectories into undamped harmonic oscillators. Only population control measures can be effective in preventing the repetitions of population size oscillations. The first oscillation is already inevitable. The time to prevent it has been lost. A stationary state is possible only following the first or the second oscillation. The optimal time of transition to a final stationary state depends on the position of the local stationary state of population size in time. This state is determined by the phase portrait in the "population size — relative population increment" plain (Allee curve). Population size in a local stationary state is assumed as the initial condition in the logistic model of population growth, and the tolerable threshold of population size is found to be 1.5 billion. The time to Lyapunov stationary state of GSES critically depends on a single parameter, which is the coefficient of population size increment at a local stationary point.

***Keywords**: civilization, global model, fuel resources, oscillatory development, stationary state.*

INTRODUCTION

The humankind is currently going through demographic, socioeconomic, and environmental crises prone with catastrophic consequences, which are unrecognized by ignoramuses and disregarded by optimists. The recent concept of "sustainable development", i.e. development that meets the needs of the present without compromising the ability of future generations to meet their own needs, is comforting; however, it cannot be helpful in searching for approaches to preventing or ameliorating the looming collapse.

Helpful in this regard may be the mathematical models of global development. Jay Wright Forrester who developed the first of such models declared his concept of global modelling at a special meeting of the US House of Representative as the following: "The human mind is not adapted to interpreting how social systems behave. In the long history of evolution it has not been necessary until very recent historical times for people to understand complex feedback systems. Social systems are far more complex and harder to understand than technological systems. Why then do we not use the same approach of making models of social systems and conducting laboratory experiments before adopting new laws and government programs? I suggest that we now do know enough to make useful models of social systems".

The shrewd investigator delineated the critically important components of the global system to include them in his World2 model, which makes the basis of a number of further global modelling attempts, including the one described in the present paper.

The paper is about long-term prospects for human civilization as it depends on the global socioeconomic system (GSES). It will be shown below that in the XXI century the humankind will face not a collapse but a profound crisis followed by recovery. In the third millennium, GSES will go through a number of developmental cycles, which will depends on power availability. Any transition to a stationary trajectory, which may be tolerable for the biosphere, is possible only after the first or some subsequent developmental cycle is completed. The logistic model of population size growth is shown to be the most relevant for such transition.

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1. Searching for ways to global equilibrium

1.1. Malthus's concept

In 1798, the English cleric and scholar Thomas Robert Malthus issues the book "An Essay of the Principle of Population" where he proposed the simplest model of population size (P) growth, which may represented with the equation:

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \varepsilon P \quad , \qquad (1)$$

where t is time, and $\varepsilon = \mathrm{const} > 0$ is the rate of natural may be called population growth factor.

The solution of Eq. 1 is:

$$P(t) = P_0 \mathrm{e}^{\varepsilon(t-t_0)}, \qquad (2),$$

where P_0 is population size at t_0, and e is the base of natural logarithm.

In classic ecological demography, the plot of an exponential increase in population size (Eq. 2) is called biotic potential curve. The increase is consistent with that when time (not resources abundance!) increases arithmetically, population size increases geometrically if there are no factors that restrain population growth. Population size is constant when $\varepsilon = 0$ and decreases when $\varepsilon < 0$.

In wild animal populations, negative correlations between ε and P are typical suggesting the existence of factors that limit population growth to an optimal size corresponding to the carrying capacity of the environment. The only species that features a positive correlation between ε and P is Homo sapiens (human intelligent). Indeed, during the last 190 years the total human population increased from ca. 1 billion in 1827 to 7.3 in 2016, the values of ε increasing too: $\varepsilon(1880) = 0{,}0065$, $\varepsilon(1945) = 0{,}0133$, $\varepsilon(1968) = 0{,}0191$, $\varepsilon(1981) = 0{,}0179$, $\varepsilon(1993) = 0{,}014$, and $\varepsilon(2006) = 0{,}0128$. Thus, human population on the Earth was increasing in 1827 through 1968 even faster than it may follow from the Malthus model. By the words of M. Mesarovich and E. Pestel who developed one of global development models, the world is affected by cancer, which is the human race.

In the model by Eq. 2, no factors can limit population growth. It is assumed on an intuitive basis that food shortage will ruin GSES and, therefore, the apocalypses may be delayed by wars, epidemics, and famines. The antihuman and unsubstantiated spirit of such assertions were the reasons for proponents of communism to criticize the Malthusian concept severely and to treat it as an antiscientific and reactionary theory.

1.2. Malthuses with computers, or prophets?[1]

In 1971–1974, J.W. Forrester and O.L. Meadows developed the first global models of GSES development, World2 and World3. The models are based on systemic dynamics principles implemented in a method of studies of complex systems having nonlinear feedbacks, which had been developed at Massachusetts Institute of Technology [32, 39]. The English economist K. Freeman who was dissatisfied with the apocalyptic prophecies derived from World3 modeling nicknamed World3 author as "Malthus with a computer". The nickname may be judged as either a reproach or a compliment. The reproach is for predicting demographic, economic and environmental catastrophes by the end of the XXI century. The compliment is for the clarity of the model providing for understanding the validity of its predictions.

The model World2 is, basically, a system of 5th-order ordinary differential equations. The right parts of the equations are defined with graphic or tabulated data presenting nonlinear relationships between the components of GSES, such as population size P, *capital investment*[2] K, the share of the agricultural capital investment X, environmental pollution Z, and nonrenewable natural resources R [32]. Equations for the above variables are constructed based on the balance principle:

$$\mathrm{d}\varphi_i/\mathrm{d}t = V_{\mathrm{i}}^{+} - V_{\mathrm{i}}^{-}, i = 1, 2, 3, 4; \qquad (3)$$

where: V_{i}^{+} and V_{i}^{-} are the rates of increases or decreases in the components of a system, and φ_i is one of the components.

In equations for the variable R, the balance principle is irrelevant. Nonrenewable resources can only decrease at a rate V_5^{-}, which depends on population size and living standards.

GSES development in 1900 through 2100 was modeled. The initial conditions were defined based on available global statistics data. The model segment related to 1900 through 1970 was represented analytically, and its parameters were determined by varying their values and tabulated relationships at accuracies defined by available historical data.

World2 computations suggested that, upon current developmental trends, the explosive development of GSES in the XX century will be followed by GSES collapse associated with the exhaustion of the unrenewable natural resources, including all sources of food, and with environmental pollution (Fig. 1).

Starting from the years 2020-2030, global human population growth is envisioned to discontinue and then, over the subsequent 75 years, population size must decrease by 2 billion. There will be left less than 1/3 of the initial amount of natural resources. By 2050, environmental pollution will be 7 to 8 fold higher than in 1970. Diminished natural and labor resources will lead by mid-XXI century to considerable decreases in industrial and agricultural outputs.

In search for means of preventing the catastrophe, J. Forrester suggested the concept of transition to global equilibrium based on zero GSES growth. Several modeling scenarios have shown that such a transition is

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[1] Christopher Freeman. Malthus with a computer, Futures, Volume 5, Issue 1, 1973, Pages 5-13, ISSN 0016-3287, https://doi.org/10.1016/0016-3287(73)90053-0. (http://www.sciencedirect.com/science/article/pii/0016328773900530).

[2] This term is adopted in the book by J.W. Forrester "World dynamics".

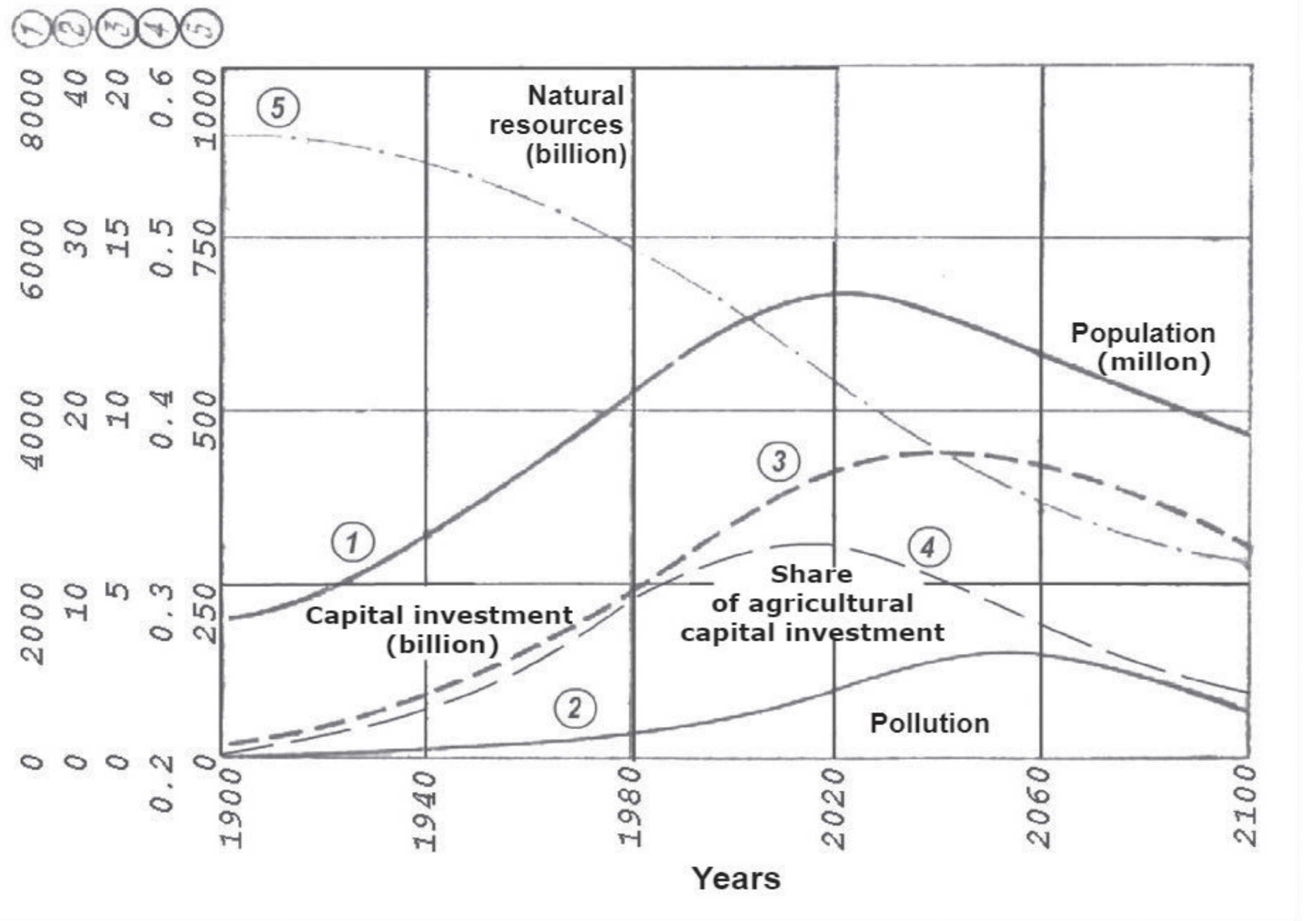

Fig. 1. The temporal variability of GSES components according to the basic scenario of World2 model [32]. The initial natural resources (100%) are assumed to amount to 900×10^9 resource units (RU)

feasible within the years 1990–2100 upon the following constraints: the consumption of the nonrenewable natural resources must decrease four times relative to its rate as of 1970; pollutants generations must decrease two times; investments in economy must decrease two times; food production, by 20%; and birth rate, by 30%. Obviously, these constrains are unrealistic.

The apocalyptic prophecy aroused much tumult in public. Critical comments, such as that GSES structure is too simple and comprises no means to control its development, motivated the Club of Rome to continue sponsoring the development of global models. The next model World3 was developed by the team lead by D.L. Meadows [39].

The model World3 comprises 12 basic first-order ODE, 16 accessory ODE designed to capture the effects of smoothing and temporal delaying of some socioeconomic parameters, and a number of algebraic and tabulated inputs. The components of the model include four age groups of human population, capital investments assigned to industrial and servicing enterprises, the areas of potentially cultivable lands, urbanized areas, soil erosion areas, environmental pollution, and nonrenewable natural resources.

The sophistication of Wold3 structure produced no significant effects on modeling results. Computations suggested once again that, in the second half of the XXI century, there must occur demographic, economic and environmental catastrophes caused by rapid population growth, food shortage, environmental pollution, and nonrenewable resources exhaustion. The only means to prevent the collapse of GSES, that is to come to “a global equilibrium”, is, according to World3, the immediate (i.e. starting from early 1970ies) implementation of the following: birth rate must not exceed death rate; population size must be stabilized at a level as of 1945 (ca. 2.6 billion) and industrial production, as of 1980; per capita resource consumption must not exceed 1/8 of the level as of 1970; the lifetime of capital investment must be increased 1.5 times, and pollutant generation per production unit must not exceed ¼ of the level as of 1970. Obviously, this all is unfeasible.

1.3. Spatially compartmentalized global models

The above global models did not account for the regional differences within GSES. The subsequent elaboration of models made them increasingly complex because of transition from pointwise (spatially homogenous) to blockwise models that were structured in spatial terms (compartmentalized). The world was regarded as not a whole, but as a differentiated entity. Novel economic, demographic, and environmental components were devised, and the previous ones were disassembled. Diverse mathematical techniques of representation of mental images of the real world were devised. The new projects included "Strategy of Survival" (M. Mesarovich and E. Pestel [40]), Latin American Model (Herrera et al. [33-35, 42]), and the Japanese "New Vision for Development" (Y. Kaya [36]).

The trust in an increasingly closer correspondence between a model and the original resulted in the emergence of monster models, which in fact obscured the principles of GSES functioning and shortened the tractable temporal ranges of modeling, e.g., to 1975–2025 in "Strategy of Survival", 1975–2100 in the Latin American model, and 1970–2010 in the Japanese model.

"Strategy of Survival"

An exemplary monster model is "Strategy of Survival", where interactions between 10 regions (North America, West Europe, Japan, Australia and South Africa, East Europe, Latin America, Middle East and North Africa, Tropic Africa, Southeast Asia, and China) are treated. Each region is represented with a system of sub-models related to economy, demography, energetics etc. For each region, 19 categories of industrial, 2 of agricultural, and 5 of energetics-related capital investments are envisioned. Separately considered are asserts related to fishery and mining industries. The region are interconnected via migration, export, and import.

The preoccupation of the authors of the model with differentiation and particularization is apparent from the following examples. In demographic sub-models, mortality and age transitions of 85 age-stratified subgroups are considered. In production sub-models, net production rates of 26 foods, including eggs, honey, and giblets, are included. In a review of reports for the Club of Rome[3], it is noted that, whereas the Meadows's model includes about one thousand equations, there are more than two hundred thousand equation in the model devised by Mesarovich and Pestel.

Clearly, the model "Strategy of Survival" violates one of the key principles of systems analysis, i.e. not all, but only the most significant relationships within a system under study should be mapped onto its model. This is because the equations included in a model cannot describe the related phenomena exactly, and data obtained by socioeconomic and environmental monitoring are burdened with noise generated by measurements and sampling errors. Since the equations are essentially nonlinear, the noise is not dampened but instead is amplified by solving them thus making the solutions probabilistic rather than deterministic [4]. Therefore, on long time intervals, the models World2 and World3, which are pointwise, in terms of T.A. Aizatullin's classification[4], are preferable over compartmentalized models.

The main inference from the model is that GSES is under the threat of not a single global catastrophe in epy mid-XXI century, but of a series of regional catastrophes at different times and in different regions due to different reasons. The "novelty" of this conclusion in association with its labor intensiveness prompted to S.D. Dadayan the metaphor "computer without Malthus" for the team of its developers [10, p. 145]. The structure of the model may be characterized as so excessively complicated that it takes months to understand what it is about if not to believe it by default. This makes it is hard to tell genuine conclusions from the input assumptions of the model.

The Latin American model of global development.

This model relates to four regions: Africa, Latin America, Asia, and developed countries. It includes five sub-models related to population, economy and housing, urbanization, education, and nutrition. The regions interact via trade and gratuitous aid. The global crisis is assumed to have already occurred because of the fallaciousness of consumer society. The crisis is not associated with natural resource exhaustion and environmental pollution. It is assumed that R&D progress will allow cost effective developing of minefields even upon their constantly decreasing productivity, that nuclear synthesis will become an inexhaustible source of energy, and that the development of waste treatment technologies will solve the environmental protection problems.

The development of each region is modeled by solving an optimization problem. The shares of capital investment and labor resources are assumed as the guiding parameters. Two scenarios are modeled. According to the first one, the developed countries refuse to provide gratuitous aid. Then the components of the developed countries sub-model must reach stationary conditions in 20-30 years after the starting time, i.e. by 1980. The same must occur ten years later in Latin America and never in Asia and Africa, even upon an optimum governance. According to the second scenario, aid is provided to developing countries starting from 1980. Ten years after that, the aid reaches 2% of the annual product of the capital generation sector of economy of developed countries. According to this scenario, a

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[3] http://www.ihst.ru/~biosphere/Mag_3/gvishiani.htm

[4] https://studopedia.ru/2_32769_tipi-matematicheskih-modeley.html

governance regimen that ensures stationary conditions of all regions is possible. In Asia and Africa, the stationary conditions are reached in about 60 years.

Thus, it has been shown, using a spatially compartmentalized global model, that economic aid provided by the developed countries to the developing regions of the world can prevent catastrophes and drive GSES to stationarity.

Global economic models

Some models are designed to tackle specific global problems. Often such models either lack some of the subsystems of the global system or include them as external or predefined variables. "Such approaches are prone with the loss of the main advantages of global modeling, i.e. the systems analysis of reciprocal influences of different factors and processes on each other. Such specialized models should be constructed by not excising of blocks from the general structure of a global models but by disaggregation of one or several blocks upon obligatory preservation, let it be even in a most aggregated mode, with the rest of the global model [11, p. 20].

A special place among economic models belongs to the project "The Future of the World Economy" run under the guidance of the Novel Laureate V. Leontief [37]. The project is based on the method of intersectorial modeling known as input-output production analysis. For each of 15 world regions, 45 sectors of economy are modeled, including 22 industry and construction sectors, 4 agriculture sectors, and sectors related to trade, services, transport, and communication. Environmental pollution is modeled with account for 8 types of pollutants and 5 waste treatment methods. The model, which comprises 2500 equations, envisions 8 scenarios of global economy development in the period of 1980–2000 and is aimed at designing the economic development of the world.

The system LINK developed by the Nobel Laureate L. Klein [12] is an agglomeration of independently designed models of countries and regions of the World, which are combined via the international trade sub-model to form a Global Model. The system includes the models of the economies of the USA (207 equations), Canada (183 equations), France (32 equations), United Kingdom (226 equations) etc. – more than 20 regional models. The system is designed to make economic prognoses for up to three years ahead.

Of special interest is the model "The Future of Civilization and the Strategy of Civilizational Partnership", which has been developed under the aegis of Pitirim Sorokin-Nikolai Kondratyev International Institute in Russia and Kazakhstan by a team of researchers [1]. The forecasting technique in this case is based on additive logistic and cyclic models. Their parameters are determined by applying the least square method to time series related to the period of 1950–2006. The model has yielded a prognosis of advances in technologies and labor force balances in 12 local civilization and countries therein. However, the model is, basically, a statistical one and thus may be regarded as fully workable only *a posteriori*, so as other similar models. The modeled prognoses for up to the year 2050 may be valid only as far as the economic situations of 1950–2007, which were used for learning, may be recapitulated.

Models of regional development

The first modeling-based reports presented to the Club of Rome, «especially "Limits to Growth" with its worldwide resonance, gave a strong impetus to global modeling efforts in 1970ies. However, the more models were being developed, the less public attention they were attracting, and thus interest to them was becoming increasingly limited to a narrow group of specialists. The Club of Rome gave heed to the reprimands related to its preoccupation with techniques and started searching for broader approaches to global problems»[5]. This resulted in a sort of inversion of the different phases of global studies: systems analysis was replaced with system approach, and mathematical models were replaced with verbal reasoning.

However, such inversions do not last for long. "Narrow" specialists went on to develop global and regional models.

The first spatially structured regional model was, perhaps, another recapitulation of World2 applied to a study of interactions of "rich" and "poor" regions of Switzerland [43].

The regional model of the system "USSR–Cities–Villages–Leningrad", which was developed at Leningrad (currently Saint-Petersburg) University, is a symbiosis of World2 and World3 models [26, 27]. Tabulated relationships between demographic, economic, and environmental processes accounted for in the models were obtained from State Statistical Records of the USSR. The model implemented the principle of priority of upper hierarchical levels over lower ones, i.e., a country can influence its regions being independent from their influences.

More detailed descriptions of the above and other important pointwise and spatially compartmentalized models may be found in the monograph "Global Models of Humankind Development" by G.V. Osipov and V.A. Lisichkin [14]. In a useful review [44] the methodology of studying of what its authors name anthropocene is discussed, and a list of publications that address socioeconomic systems modelling is presented.

1.4. Restoring the finite natural resources

A number of papers published in the USSR and the Russian Federation addressed the issue of searching for algorithms that can lead global models to stationary conditions

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[5] http://www.ihst.ru/~biosphere/Mag_3/gvishiani.htm

(global equilibrium). The authors did not construct novel models but rather modified the models World2 and World3. The studies were based on the idea of reallocation of world capital investment investment in favor of the industrial restoration of spent unrenewable natural resources and the generation of useful products from pollutants. This was assumed as implementable worldwide during the nearest 30–50 years of model time, i.e. the period predicted by the developers of World2 and World3 to precede the global catastrophe.

The first such modification of World2 was suggested by V.A. Yegorov et al. [11]. The authors introduced to the right parts of the equations that capture the nonrenewable resources and environmental pollution the additive control members (KU_R^0/C_R^0) and (KU_Z^0/C_Z^0), and to the right part of the equation that captures the agricultural capital investment they introduced the multiplier (1-U_X^0). The parameters U_R^0, U_Z^0, U_X^0 are the shares of *capital investment K* that are allocated to restoration of natural resources, mitigation of environmental pollution, and management of agriculture, respectively. C_R^0= 0,3 and C_Z^0= 0,4 are the amounts of capital investment units (CU) that are required to restore one unit of resources and eliminate one unit of pollution. The controls for U_R^0, U_Z^0 and U_X^0 are functions of time. After they have been defined, it is possible to reallocate capital investment K between traditional and novel industrial sectors. To define the control functions, the optimum control problem have to be solved by defining a criterion and finding a function that maximizes the criterion. This variational problem was solved for the period from 1975 to 2100, and the solution suggested that it is possible to prevent a global catastrophe in the XXI century. For that, the capital investment of enterprises intended for restoration of resources and prevention of pollution must increase annually to become in the XXI century comparable to the capital investment of all industries "…that is, human labor intended for prevention of the economic crisis must be quantitatively comparable with human labor in all other fields of human activities" [11, p. 140]. The questions however remains how long can the restoration of resources last after the year 2100. The resources are finite all over the geographic envelope and, according to World2 algorithm, are consumed for production and cannot all be restored completely.

A thorough modification of the global model World2 and World3 was performed by a research group led by V.M. Matrosov. In addition to the traditional World2 components, the modification included new variables, such as technological progress, political tension, and total plant biomass, which influence capital investment reallocation in favor of restoration of the nonrenewable resources and correction of agricultural capital investment as it interpreted by the V.N. Yegorov. No optimization procedures were used in the model. Nevertheless, upon the use of only the functional relations between model components, stable stationary conditions of GSES were reached. The algorithm of the model is advantageous in taking account for causal relationships between technological progress, political tension and ecological variables and is disadvantageous in adopting the hypothesis that it is possible, at least in the nearest decades, to restore the nonrenewable resources, except for rare metals.

One more World2 modification, perhaps the most interesting one, is designed by S.A. Makhov [17]. In this model, so as in Yegorov's one, a part of capital investment is allocated to restoration of resources and to prevention of pollution; however, no controls for agriculture are introduced. The controls U_R and U_Z are not functions of time. To define them, World2 is supplemented with two equations:

$$\frac{\mathrm{d}U_R}{\mathrm{d}t}=\frac{G_R(R_R)-U_R}{T_{UR}}\ , \qquad (4)$$

and

$$\frac{\mathrm{d}U_z}{\mathrm{d}t}=\frac{G_z(Z_s)-U_z}{T_{UZ}}\ , \qquad (5)$$

where: G_R and G_Z are investments in industries for restoration of nonrenewable resources and for removal of pollutants from the environment; R_R and Z_s are the shares of the remaining resources and of the specific pollution (these are World2 variables); and T_{UR} and T_{UZ} are the periods of the losses of the capital investment of the respective industrial sectors.

For G_R (R_R) and G_Z(Z_s), functions have been found that guarantee stationary conditions of GSES, and their parameters have been determined. In particular, it has been established that G_R (R_R) must be hyperbolic, whereas G_Z(Z_s) must be linear. The equations of the modified World2 model were integrated on the period between the years 1900 and 2200. It was found that transition to stationarity must occur before the year 2150. It has been also determined that "good" stationary solutions are possible upon G_Z= 0, i.e. the constancy of pollution level. Possibilities for such stationary regimens have been shown to exist only if the industries designed for restoration of resources and elimination of pollution re launched no later than in 2030. Regretfully, such bright prospects are based, once again, on the assumption that the capital investment of the newly developed industries in the XXI century is comparable with that of the traditional industries.

2. Developmental cycles are typical for the evolution of civilization

2.1. Cyclic phenomena in population ecology

From the standpoint of population ecology, the apocalypse predicted by Wold2 and World3 models does not seem fatal. The rational for this assertion is as follows. The two known types of population growth are characterized with J- and S-like growth curves [20]. With a J-like curve, a population first increases exponentially, and then, due to negative feedback from the environment, the growth discontinues. The population exhausts available resources. Proliferation ceases and mortality increases.

A decrease in population size is followed by relaxation oscillations (Fig. $2A_1$, A_2). Many species featuring complex and lengthy life cycles exhibit S-like curves for changes in the sizes of their populations. A population first grows, and then its size undergoes damped oscillations near some equilibrium level (Fig. $2B_2$, B_3). The level is the maximum corresponding to the carrying capacity of the environment.

Two causes of oscillations of animal populations are envisioned [20]. The first cause is that nutrients and other vital resources may have accumulated before the start of the S-growth of a population. For a time, organisms have sufficient resources for overshooting the maximum population size that the environment can support constantly. The second cause relates to a lag between population size increase under favorable conditions and the negative feedback from the environment, which develops when overpopulation is achieved. The lag, which is roughly equivalent to the maturation period of the organisms, makes it possible for the population to exceed the maximum size sustainable by the environment.

The same factors must be at work when it comes to the humankind. As a component of fauna, the human race cannot but obey the laws valid for the whole biosphere. Fossil fuels, ores and other resources, which are consumed by humans due to technological advances, have been accumulating over geological epochs and today sustain human population size above the level that the environment can bear on a constant basis.

According to E.P. Odum's opinion on this matter (see [20]), the Mankind has two options. The first one is to allow the unlimited growth of population until its density will exceed limits determined by the availability of food and other resources. After that, most humans will die or fall into misery until population density will decrease (or limits increase, if possible). This is the time when more population bursts may occur if no control measures will be taken (Fig. 3). The other options is to acknowledge that overpopulation is the problem. By taking responsibility for it, humans will be able take appropriate measures, such as global birth control, limited land use, environmental protection and restoration, and refusal from stimuli for economic growth.

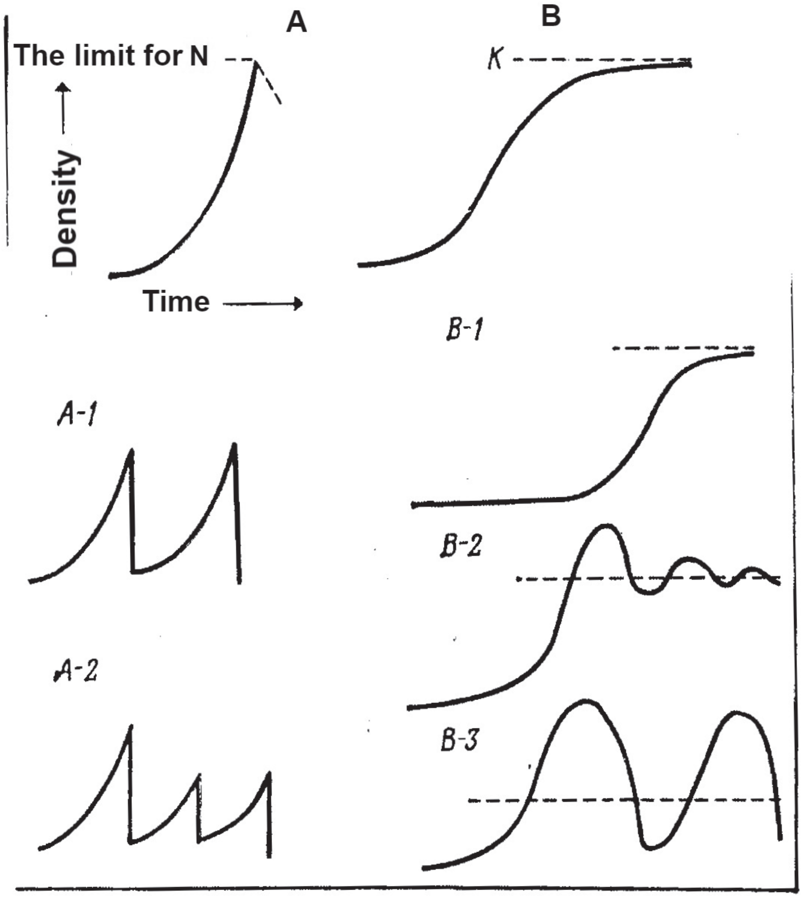

Fig. 2. Examples of population growth curves [20]. A – Exponential growth: the J-curve and variations thereof. B – Logistic growth: the S-curve and variations thereof

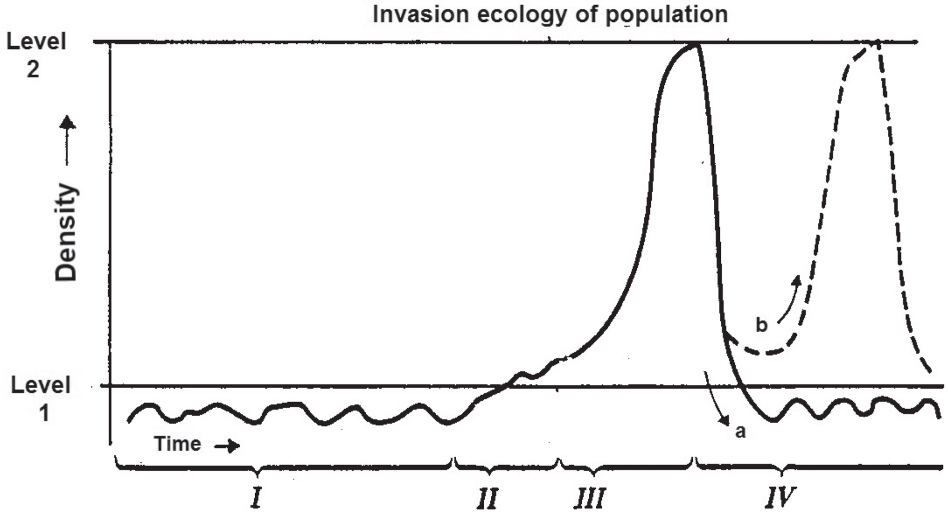

Fig. 3. Changes in population size of the Australian psyllid *Cardiaspina albitextura*, which feeds on the eucalyptus *Eucalyptus blakelyi* [20]. Normally, population density is limited by the combination of factors, such as weather, predators, parasites, which may be either dependent on or independent from the density, and thus is stabilized at a relative low level. Occasionally, the population evades the natural regulation and exhibits overshoots to higher density levels

2.2. Estimating the critical size of global human population

The estimate is based on the biospheric concept of the development of GSES. The concept put forward by V.G. Gorshkov and K. Ya. Kontratyev [8, 13] is derived from the theory of natural biological regulation. The authors believe that the biosphere is able to remain stable, i.e., to compensate for any disturbances caused by human activities as far as the consumption of the biotic output by humans is within ca. 1%. The rest 99% of the output is required to stabilize the environment. The authors estimate that the 1% threshold was exceeded early in the XX century. In the recent decades, humans directly use 6-8% of the biotic output. Moreover, 30% to 32% of the annual output of the "intact" biota is consumed by humans indirectly, i.e. by replacing natural biocenosises with agrobiocenosises in combination with urbanization, desertification and so forth [13].

The critical size of global human population may be calculated based on the estimates of the primary output of the biosphere and of the nutritional norm of human population with account for the Lindeman-Odum "10% law".

Several estimates of the primary output of the biosphere have been made. According to E. Odum [20], the productivity of the terrestrial biomes is $57.4 \cdot 10^{16}$ kcal/year, and of the marine biomes, $43.6 \cdot 10^{16}$ kcal/year. Assuming that the energy value of terrestrial plants is 4.5 kcal per 1 g of dry matter, the annual output of the terrestrial biomes may be estimated as amounting to $127 \cdot 10^9$ tons of dry matter, and of the marine biomes, to $97 \cdot 10^9$ tons. Tentative estimates of annual net terrestrial and marine outputs are $63 \cdot 10^9$ and $48 \cdot 10^9$ tons of dry matter, respectively.

According to Whittaker and Likens (see [5]), the net annual primary output of the biosphere is $164 \cdot 10^9$ tons of dry organic matter. R.H. Whittaker's estimate is $170 \cdot 10^9$ tons, including $115 \cdot 10^9$ and $55 \cdot 10^9$ tons attributed to the terrestrial and marine ecosystems respectively (see [23]). F. Ramade [23] thinks that these estimates are inflated. He prefers the ones suggested by P. Duvigneaud: $83 \cdot 10^9$ for the entire biosphere, $53 \cdot 10^9$ for terrestrial biomes and $30 \cdot 10^9$ for oceans, which is close to Odum's estimates.

Let us now apply the Lindeman-Odum law to the trophic chain "primary producers – herbivores – humans". The law posits that the output of a trophic chain link is 10% of its input. The rest 90% is dissipated by ecological metabolism. The primary annual output amounting to $53 \cdot 10^9$ tons of dry matter is equivalent to $2.385 \cdot 10^{17}$ kcal/year. With account for the above assumption, the 1% tolerable disturbance threshold of the biosphere is $2.385 \cdot 10^{15}$ kcal/year.

An equivalent of the annual nutritional minimum for a human is 230 kg of wheat. This corresponds to 770000 kcal/year (2110 kcal/day). Nutritional norms depend on human age and occupation, that is (kcal/day): 700-900 for infants, 1000-1300 for children aged 1 to 3 years, 1500–1900 for children aged 3 to 8 years, 2000–2400 for children aged 8 to 10 years, 2500–3500 for adolescents, 3000 for sedentary workers, 3500 for machine operators, and 4000–5000 for people employed in hard physical work. With account for typical proportions of the above population groups, 3800 kcal/day (1387000 kcal/year) may be assumed as an average.

The critical population size sustainable by the biosphere is defined as the ratio of 1% of its primary output and the average human nutritional norm. This will make 1.73 billion people.

2.3. The global energy resource potential

The energy resource potential, by analogy with the land resource potential, is a component of the natural resource potential. It may be regarded as the totality of energy resources available at given level of technologies and socioeconomic relationships. The potential includes both renewable and nonrenewable resources and increases in the course of the development of GSES.

During the Paleolithic, humans obtained energy from the renewable resources of the intact biosphere by hunting, foraging and plants burning of. The size of human population in those times was 200–300 thousand. Fire was used for cooking and rewarming (about 40% of total energy consumption); however, this energy could not compensate for expenses required to maintain temperature homeostasis [18].

In the Neolithic and Bronze Ages, the energy turnover of human GSES significantly increased. By this time, the traditional rural GSES developed based on agriculture and cattle breeding. About 10 thousand years ago, human population reached 5 million people.

Later on, in slave-owning and feudal societies, wind and water energy resources were harnessed. By the time of formation of the Rome Empire, human population reached 150 million, and by 1650, 500 million people [23].

In the Industrial Era, when steam and gas engines, turbines, and electric generators and motors were invented, energy supplies for human GSES originated mainly from fossil hydrocarbons. The rate of their extraction increased. In line with increasing energy availability, human population increased exponentially to reach 7.3 billion people by January 1, 2016.

In the Postindustrial Era, controlled thermonuclear power is expected to supplement nuclear power and thus to solve forever the problem of energy supplies. The question arises what law will determine changes in human population size under such conditions.

The development of productive forces is limited by natural resources according to the law of decreasing resource availability. Indeed, for a certain type of

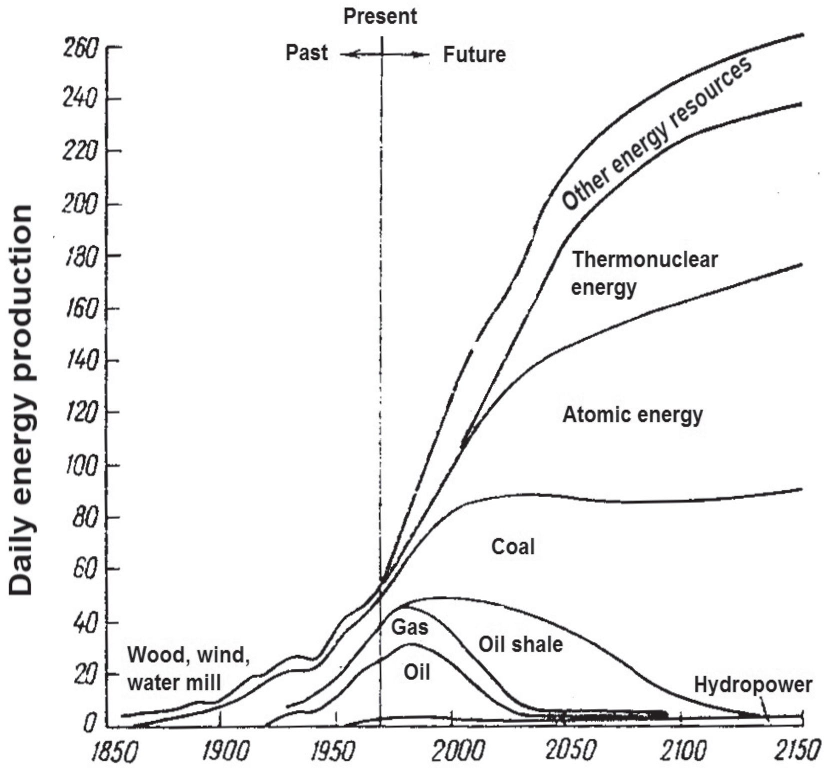

Fig. 4. Exponential growth of energy production as a sum of logistic curves related to different sources [2]. The scale on the left shows dimensionless orders of magnitude

socioeconomic system equipped with a given repertoire of technologies natural resources become increasingly costly in terms of energy spent to obtain them from dwindling available stores [23]. Productive forces develop gradually until resources become exhausted. This is followed by a crisis, which becomes resolved due to revolutionary changes in productive forces brought about by scientific and industrial revolutions. The verbal models of limited economic growth are usually illustrated with an S-like logistic curve, which shows how the initial exponential growth gradually transforms into an asymptotic approach to a limit featured by a given socioeconomic system.

E.A. Arab-Ogly suggested a series of logistic models of power availability, which were used to construct a verbal model of exponentially growing power availability [2, p. 211]. This approach has three shortcomings.

The first shortcoming is that the logistic models of changes in energy resource potentials related to renewable and renewable resources are treated on equal terms (Fig. 4).

In his polemics with the authors of World2 and World3, E.A. Arab-Ogly declared the following: "One needs no special mathematical imagination to see that the exponential growth of aggregated parameters can last much longer than the separate components of the resulting aggregate can grow. An exponent is formed in such a case by a series of logistic curves. This may be confirmed, e.g., by that the exponential growth of energy production lasting far beyond foreseeable future is formed by a sequential involvement of the mechanical energy of humans and animals, wind energy, water energy, thermal energy obtained by wood, coal, oil and gas combustion, nuclear energy, and thermonuclear energy. This is true even more with regard to such economic parameters as gross national product, per capita national product, working efficiency etc." [2, p. 210-211].

However, the chemical energy of life is derived by photosynthesis from the sunlight energy, then is transmitted via food chains up to humans and is assimilated and dissipated by ecological metabolism. The chemical energy of food is what sustains human activities at all of the stages of the development of the humankind. This energy is limited by the productivity of the biosphere. World2 and Wold3 models take account for this important aspect of life. They treat separately the energy of food and the nonrenewable resources consumed by industry.

The second shortcoming is underestimation of shale oil stores and overestimation of coal stores. The logistic curve attributed to coal should be attributable to shale oil and vice versa.

The third shortcoming of the model of the exponential growth of power availability is that the use of thermonuclear power refutes, albeit in an indirect way, the law of decrease in the potential of natural resources. For the sake of justice, it should be mentioned however that in Fig. 4 its author timidly bends the energetic exponent towards a logistic curve. Another Sun cannot be ignited on the planet Earth.

One more remark relates to the idea of restoration of nonrenewable natural resources as it is realized in World2 and World3. The authors of the idea ignore the fact that the resources include the material and the energetic components. To recover secondary raw materials, energy is consumed. The nonrenewable fuel resources include hydrocarbons, which store the chemical energy generated by photosynthesis and assimilated by consumer organisms over the past geological epochs, whereas the nuclear fuel is a sort of ash of long burnt-out stars where light atoms collisions formed the atoms of uranium, while the hydrogen fuel, the oldest of fuels, is a sort of ash of the Big Bang (according to G.A. Gamov).

According to one of formulations of the Second Law of Thermodynamics, energy transformation processes can be spontaneous only upon energy transformation from its concentrated to dissipated forms. Fossil fuels feature low entropy and "high-quality" energy, which is suitable for being transformed into useful work. Fuel combustion is a spontaneous process associated with dissipation of energy and reduction of its "quality". According to the fundamental asymmetry of Nature, the quality of energy cannot be transformed from low to high. Therefore, fossil fuel stores cannot be restored. An objective of civilization is to find means for more efficient management of high-quality energy that is to decrease entropy production.

2.4. The initial reserves of resources in the models World2 and World2-MC

World2 algorithm may be used to confirm E. Odum's hypothesis that civilization may develop in cycles. The algorithm has been published [32], and its implementation using programming DYNAMO language facilitated its implementation in MathCad environment [29]. The latter implementation will be called World2-MC hereinafter. It was compared with the original World2 (Fig. 1) by solving the same problems within the 1900–2100 interval. The solutions were identical.

In World2, nonrenewable fuel and non-fuel mineral resources are not distinguished, and their initial reserves R_0 are defined in relative terms. The unit of resources (resource unit, RU) is assumed to amount to the annual resource consumption in the basal year 1970. It is assumed that at the basal annual consumption the resources are sufficient for 250 years. It remains unclear, however, what method was used to make an integral assessment of numerous non-fuel resources, such as common and rare metals, agrochemical and chemical raw materials, construction materials etc.

The uncertainty of the integral estimate of non-fuel resources and the primary importance of combustible fossils as energy sources are arguments in favor of a revision of the basal condition $R_0 = 9 \cdot 10^{11}$ RU adopted in World2.

In the basal World2-MC scenarios, R_0 is defined with account for world resources of oil, gas and coal all lumped under the term “traditional fuel and energy resources”. Their reserves are well assessed and their estimates, which are periodically revised, are expressed with CI units, i.e. Joules. Besides that, the possibility to increase fuel resources with promising sources, such as shale, bituminous sand, and nuclear and thermonuclear energy, is stipulated. To preserve links between World2 and World2-MC, let us still regard the year 1970 as basal, and resource consumption in this year as resource unit (RU). The numerical estimates of RU are derived from plots shown in Figs. 5 and 6. The plots were also used World2-MC validation.

In devising the scenarios of the development of GSES, the algorithm of calculating the period of full exhaustion of fuel resources is of primary importance. The algorithm is as the following. The resources “oil”, “oil + gas = mobile hydrocarbons”, “mobile hydrocarbons + coal = traditional fuel resources”, “traditional fuel resources + shale oil = hydrocarbon fuel”, and “traditional fuel resources + nuclear and thermonuclear energy = future fuel resources” are taken into account consecutively. The terms R_m and R_n, V_m and V_n, and τ_m and τ_n designate reserves, consumption rates, and exhaustion periods of the m-th and n-th resource respectively; $R\delta n$ is the amount of the n-th resource, which is consumed during the time of exhaustion of the m-th resource; $R\Delta n$ is the residue of the n-th resource left after the exhaustion of the m-th resource; V_Σ is the rate of consumption of the n-th resource after the exhaustion of the m-th resource; and τ_s is the period of exhaustion of the n-th resource after the exhaustion of the m-th resource. With this notation:

$$
\begin{aligned}
&\tau_m = R_m / V_m \\
&R_{\delta n} = V_n \times \tau_m \\
&R_{\Delta n} = R_n - R_{\delta n} \\
&V_\Sigma = V_m + V_n \\
&\tau_s = R_{\Delta n} / V_\Sigma \\
&\tau_n = \tau_m + \tau_s
\end{aligned}
\tag{6}
$$

Now let us designate the initial conditions for the nonrenewable resources in the models World2 and World2-MC as $R_0 = 9 \cdot 10^{11}$ RU and R_0^* and as $\tau_m = 250$ years and τ_n^* (the periods of exhaustion of the resources in the respective models), respectively. R_0^* is found by solving the proportion

$$R_0 / R_0^* = \tau_m / \tau_n^* . \tag{7}$$

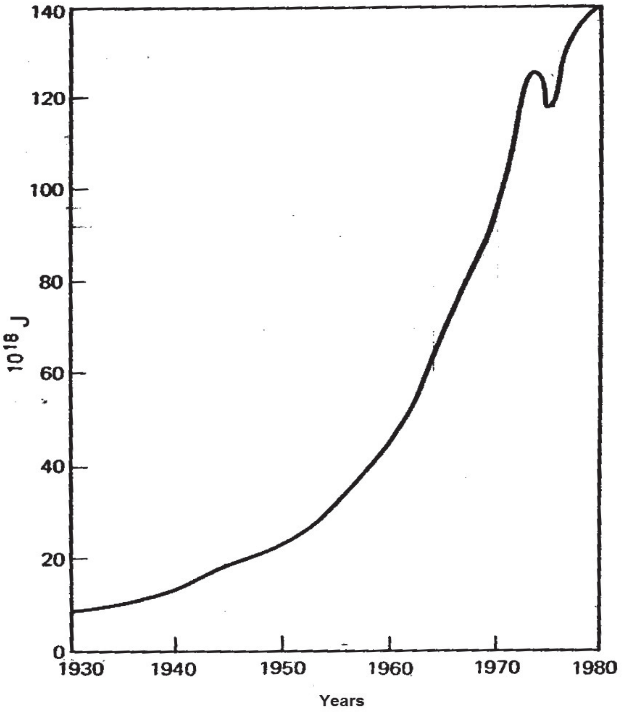

Fig. 5. Global oil production (according to UN and US Bureau of Mines) [31]. The calculated fuel efficiency is $9 \cdot 10^9$ J/barrel

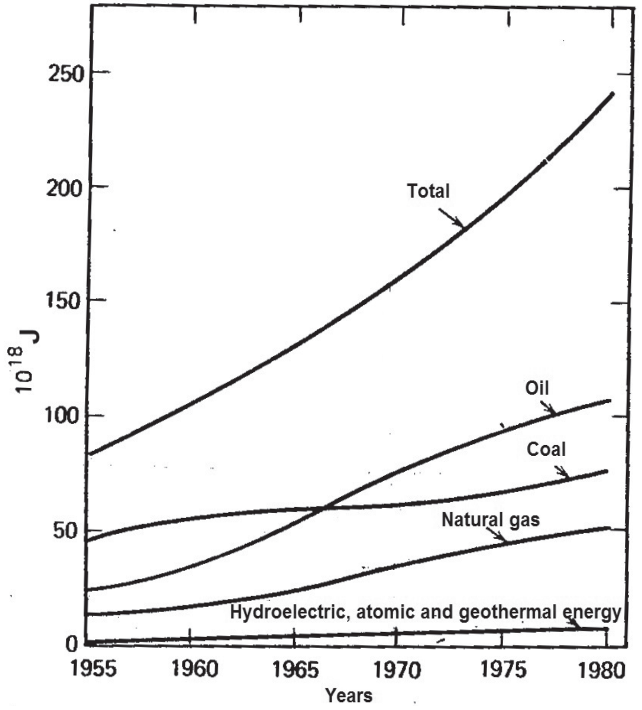

Fig. 6. Global consumption of different energy sources (according to UN) [31]

An estimate of recoverable oil and gas resources, which is one of the most reliable a close by its time to the basal year 1970, was published in the proceedings of World Energy Conference held in 1980 (see [31]). Assuming that the caloric value of oil is 44 MJ/kg, of gas is 40.8 MJ/m^3, and of coal is 29.4 MJ/kg, oil reserves $R_{1980}^{(oil)}$ are equivalent to $1.5 \cdot 10^{22}$ J; gas reserves $R_{1980}^{(gas)}$ to $1.1 \cdot 10^{22}$ J, and coal reserves $R_{1980}^{(coal)}$ to $21 \cdot 10^{22}$ J.

The estimates corresponding to the year 1900 may be obtained by the integration of the plot of oil recovery (Fig. 5) over the interval from 1930 to 1980 years, and of that of gas and coal recovery (Fig. 6) over the interval from 1955 to 1980 years. This will make $\Delta R^{(oil)} = 0.25 \cdot 10^{22}$ J, $\Delta R^{(gas)} = 0.07 \cdot 10^{22}$ J, and $\Delta R^{(coal)} = 0.23 \cdot 10^{22}$ J. Thus, the world reserves of mobile hydrocarbons are estimated as $R_{1900}^{(oil)} \approx 1.75 \cdot 10^{22}$ J and $R_{1900}^{(gas)} \approx 1.2 \cdot 10^{22}$ J.

Upon the rates of consumption of oil and gas in 1970 estimated as $0.95 \cdot 10^{20}$ J/year and $0.35 \cdot 10^{20}$ J/year respectively, their reserves will be sufficient for consumption during 184 and 343 years respectively. Upon the assumption that gas will be consumed at the same rate when it will replace oil after the exhaustion of oil reserves, the Eqs. (6) and (7) suggest that mobile hydrocarbons will be exhausted in 227 years and that $R_0^* = 11.1 \cdot 10^{11}$ RU. This estimate is close to $9 \cdot 10^{11}$ RU assumed in World2.

It was estimated at the World Energy Conference that recoverable coal reserves amount to 13800 billion tons. This figure is likely inflated. By P. Averitt's estimate, recoverable coal reserves may be as high as 7135 billion tons, which is equivalent to $21 \cdot 10^{22}$ J (see [31, p. 59]). The recoverable reserves are assumed to be those present in rows that are not less than 30 cm thick and not more than 2 km deep, with account for that it is impossible to recover all coal and that 50% recovery is rated as good [31]. Upon coal consumption rate $0.6 \cdot 10^{20}$ J in 1970, coal reserves will be sufficient for 3500 years. Upon the assumptions that coal will replace oil and gas after their reserves will be exhausted, and that the total rate of consumption of the traditional fuels will not change, all fuels will be exhausted, according to Eqs. (6) and (7), in 1034 years, and R_0^* is equivalent to $37.2 \cdot 10^{11}$ RU. Thus, this initial assumption of World2 is 4.16-fold understated.

The reserves of oil, gas and coal in 2014 amounted, according to BP Statistical Review of World Energy 2015, to 239.8 billion tons, 187.1 trillion m^3, and 891.5 billion tons respectively. These values are equivalent to $L_{2014}^{(oil)} = 1.06 \cdot 10^{22}$ J, $L_{2014}^{(gas)} = 0.76 \cdot 10^{22}$ J, and $L_{2014}^{(coal)} = 26.2 \cdot 10^{22}$ J.

With the rates of resource consumption assumes to be the same as in 1970, it may be estimated that $= 0.65 \cdot 10^{22}$ J, $R_{2014}^{(gas)} = 0.6 \cdot 10^{22}$ J, $R_{2014}^{(coal)} = 25.41 \cdot 10^{22}$ J (the initial reserves being $R_{1900}^{(oil)} = 1.75 \cdot 10^{22}$ J, $R_{1900}^{(gas)} = 1.2 \cdot 10^{22}$ J, and $R_{1900}^{(coal)} = 26 \cdot 10^{22}$ J).

Thus, the biases $\Delta = L\text{-}R$ are estimated as $\Delta^{(oil)} = 0.41 \cdot 10^{22}$ J and $\Delta^{(gas)} = 0.16 \cdot 10^{22}$ J. Positive biases may be caused by new hydrocarbon deposits discovered after 1980, such the Shtokman Field. In any case, such bia– ses only increase the estimates of R_0^*. Coal bias was not calculated because of tenfold discrepancies between the estimates of coal reserves. The reasons of the discrepancies may include different ideas about coal production efficiency and uncertainties concerning the fuel efficiency of coal, which is different in brown coal (15 MJ/kg), black coal (22 MJ/kg), and anthracite (29 MJ/kg).

Notably, fossil fuels are not limited to mobile hydrocarbons (Table 1)

Table. 1

Potential fossil fuel reserves [31]

Combustible fossils	**Total reserves (10^{22} J)**	**Recoverable reserves (10^{22} J)**
Coal	42	21
Oil and gas	2.1	2.6
Dead oil	2.5	0–?
Unstripped oil (bitumen sand)	5.0	0.5–2.5
Nontraditional natural gas	10+	0.07–?
Combustible shale (above 40 L/ton)	200	1.0–?
Combustible shale (below 40 L/ton)	10000	?
Global oil and gas consumption in 1983	*0.018*	
Global energy consumption in 1983	*0.03*	

2.5. Model scenarios of the development of GSES upon expanding the energy resource potential with traditional fuel resources

For World2-MC scenarios realization, the same initial conditions as for World2 are stipulated except for the nonrenewable resources: $P_0 = 1.65 \cdot 10^9$ people; $K_0 = 0{,}4 \cdot 10^9$ CU (it is assumed that, in 1900 compared with 1970, four times less per capita capital investment was available); $X_0 = 0.2$; R_0^* depends of the scenario chosen; and $Z_0 = 0.2 \cdot 10^9$ PU (it assumed that, in 1990 compared with 1970, per capita pollution was eight time lower). The subscript * at R_0 will be omitted hereinafter.

Let us first consider four scenarios featuring fixed values of the global energy resource potential. The first scenario will be associated with the current estimates of mobile hydrocarbon reserves, which at the current rate of their consumption will be exhausted in 250 years, i.e. by 2150. Their reserves are assumed as 100%. The starting condition is $R_0 = 900 \cdot 10^9$ RU.

The second scenario models the prospect of expanding of energy resource potential due to oil and gas resources found on the shelves and the continental slopes of the World Ocean. Mobile hydrocarbon reserves are assumed to increase to 150% thus making them sufficient for 375 years, that is till the year 2275, and the initial condition is $R_0 = 1350 \cdot 10^9$ RU.

The third scenario models the situation of using coal to substitute for the exhausted mobile hydrocarbon recourses; however, coal production is limited by the efficiency of available technologies. Fuel reserves are assumed to increase to 300% in this case, making them sufficient for 700 years, i.e. till the year 2600; and the initial condition is $R_0 = 2700 \cdot 10^9$ RU.

In the fourth scenario, requirements to the threshold efficiency of coal production are reduced to make coal stores sufficient for 1000 years, i.e. till the year 2900; and the initial condition is $R_0 = 3600 \cdot 10^9$ RU.

With regard to the above scenarios, additional comments are required.

1. According to World2, «Natural resources are a system level. The only rate of flow is the outgoing usage rate. As defined here, natural resources include only those nonreplacable materials in the earth. They do not include wood and any products that can be grown and replenished, for the latter are classed as part of the agricultural sector» [32].

However, the fuel resources of GSES are the sum R of renewable and nonrenewable resources. Therefore, the equation for the resources should be:

$$\frac{\mathrm{d}R}{\mathrm{d}t} = V^+ - V^-,$$

where: V^+ is the primary productivity of terrestrial systems (the rate of assimilation of solar energy by terrestrial plants); and V^- is the rate of consumption of the nonrenewable fuel resources

The annual productivity of the terrestrial ecosystems is estimated as $53 \cdot 10^9$ tons of dry matter, which is equivalent to 10^{19} J/year. The rate of consumption of the traditional nonrenewable fuel resources in the reference year 1970 was $1.9 \cdot 10^{20}$ J/year. This is one order of magnitude higher that the productivity of the terrestrial ecosystems. This difference in scales makes it possible to simplify the above resource equation:

$$\frac{\mathrm{d}R}{\mathrm{d}t} \approx -V^-.$$

In this way, the productivity of the terrestrial ecosystem is adopted by default (implicitly) in World2-MC. This approach is useful for explaining the stationary flux of population when resources and population size are constant, and GSES exists at the expense of consumption of the renewable resources, the population size being less than 1.5 billion people.

2. People obtain foods from agricultural lands, which are withdrawn from the native biosphere and feature the productivity estimated to amount to $9.1 \cdot 10^9$ tons/year [24]. This estimate is 5.8 times less than the productivity of the terrestrial ecosystems. Therefore, the equivalence of agricultural production and the renewable resources of the terrestrial ecosystems, which is assumed in World2, is false. In World2-MC, the agricultural production is but an apparent part of renewable resources accounted for by default.

Modelling based on the above premises (Fig. 7 and 8; Table 2) suggest that an expansion of the energy resource potential in GSES is associated with oscillations of all components of the potential. The number of oscillations increases as the amount of available resources increases. Upon increasing the resources to 150% vs. the norm adopted in World2 ($9 \text{-} 10^{11}$ RU), two oscillations of population size emerge. With 300%, there are three oscillations, and with 400%, there are four. The amplitudes of the oscillations are 2 to 5 billion people. The time of the peak of the first oscillation will not shift significantly with increasing the potential (from 2018 to 2033), and that of the second and third oscillation will shift within the limits of 33 and 45 years respectively.

Notably, the numbers of the oscillations of environmental pollution and of the share of the agricultural capital investment are always one unity less than the number of oscillations of human population.

Nonrenewable natural resources do not limit population growth, which is limited by agricultural production and environmental pollution. These two factors act perpetually over all time intervals when population decreases. The maximums and minimums of pollution and agricultural capital investment a delayed by one or two decades relative to those of population.

The capital investment of economy gradually decrease in all scenarios and correlate with decreased reserves of nonrenewable resources. Small oscillations of capital investment are phase-shifted and thus lag behind the oscillations of population. This likely reflects deficits of labor resources during the descending phases of GSES cycles.

In each of the scenarios, the final oscillation of population size is followed by its stabilization, which occurs in 437 years in the scenario with a 150% expansion of the energy resource potential, in 609 years with a 300% expansion, and in 1000 years with a 400% expansion. Stabilized is a level between 1.3 and 1.5 billion people, probably the maximum number of humans sustainable by the natural and socioeconomic environments.

Along with population size, other components of GSES also reach stationary conditions (Table 3).

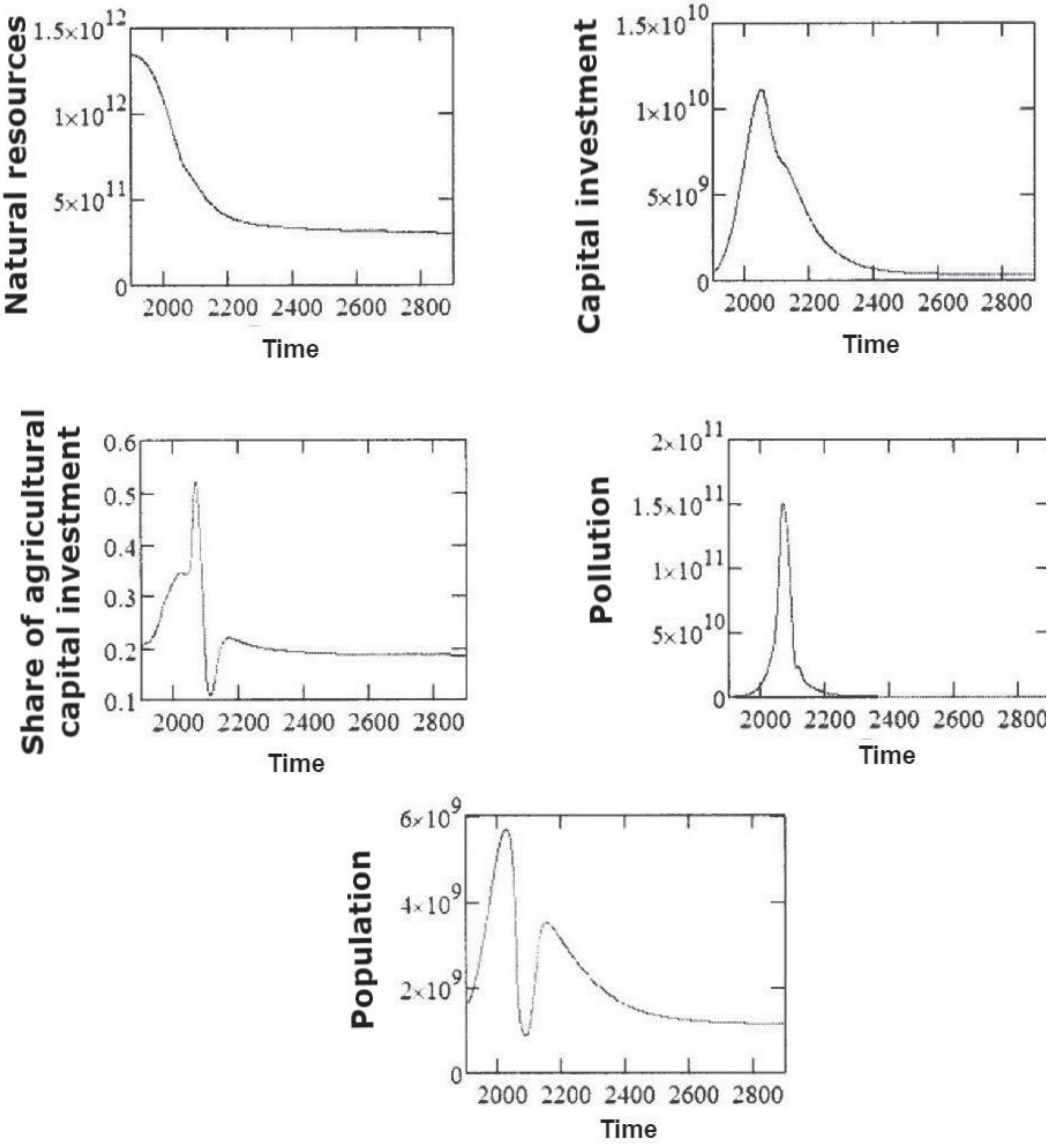

Fig. 7. Time-dependent changes in GSES components modeled with World2-MC at $R = 1350 \cdot 10^9$ RU (the 150% scenario). See text for explanations

The possibility of a cyclic development of GSES followed by a stationary phase has been independently demonstrated in [44] based on very different premises. The authors used the classic Volterra-Lotka model of prey-predator relationships supplemented with interspecies competition between preys. The idea to treat the environment as a prey and the human population as a predator and to use the Volterra model of biological systems comprising producers, consumers and substrates (resources) proved to be fruitful (a similar model was discussed in the monograph by Yu.M. Svirezhev and D.O. Logofet [25, p. 130-169]). The authors of [44] treated the property-related structure of human society, which consists of "rich men" and "common people", by analogy with the species structure of a biological community. Birth and death rates in different strata of a human population were assumed to depend on the allocation of production, which is generated by common people and distributed by rich men. The authors have shown that excessive exploitation of resources and inequality of incomes are the

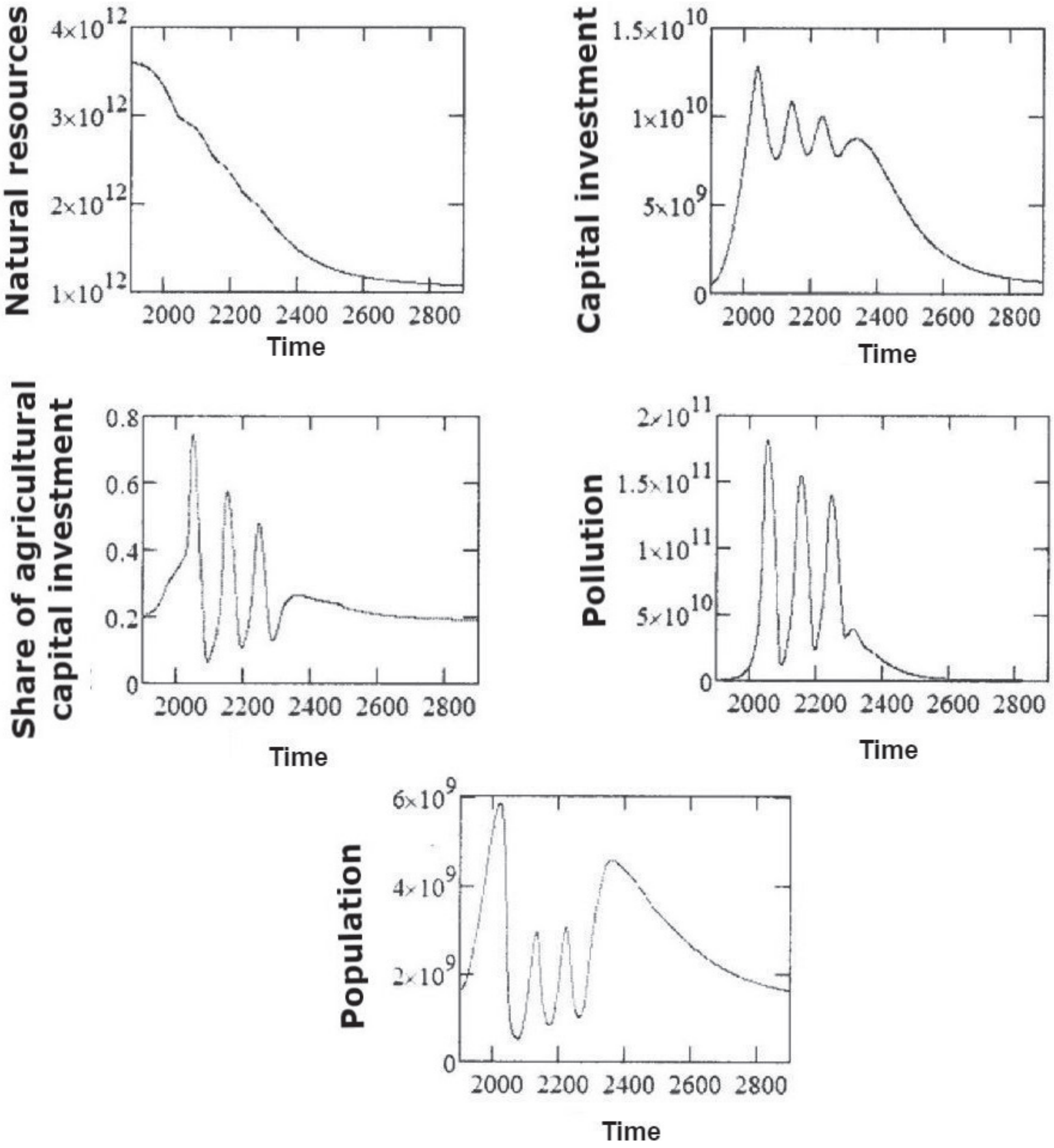

Fig. 8. Time-dependent changes in GSES components modeled with World2-MC at $R = 3600 \cdot 10^9$ RU (the 400% scenario). See text for explanations

Table 2

The maximums and minimums of global populations and the years of their achievement according to World-2MC scenarios of global development

R, % of the reference value	Year	Population size P · 10^9	
		Min	Max
100	1900	1.65	
	2022		5.29
	2450	1.25	
150	1900	1.65	
	2033		5.62
	2084	0.87	
	2163		3.54
	2600	1.26	
300	1900	1.65	
	2021		5.81
	2075	0.54	
	2132		3.05
	2179	0.97	
	2271		4.43
	2880	1.3	
400	1900	1.65	
	2018		5.83
	2075	0.51	
	2130		2.95
	2170	0.83	
	2226		3.08
	2265	1.01	
	2363		4.53
	2900	1.5	

Table. 3

The years of achievement and the levels of stabilization of GSES, according to different World2-MC scenarios [29]

Scenario	Year	Population, billion people	Nonrenewable natural resources	Capital investment	The share of agricultural capital investment	Environmental pollution
150%	2600	1.26	$3.10 \cdot 10^{11}$	$3.23 \cdot 10^8$	0.18	$2.77 \cdot 10^8$
300%	2880	1.30	$7.58 \cdot 10^{11}$	$4.82 \cdot 10^8$	0.18	$3.33 \cdot 10^8$
400%	2900*	1.50	$10.8 \cdot 10^{11}$	$6.96 \cdot 10^8$	0.19	$4.82 \cdot 10^8$

* The system is not stabilized completely on a 1000 years interval

two independent factors of a series of catastrophic events, and openly declared the necessity to level off incomes and to reduce resource spending.

2.6. Model scenarios of GSES development upon expanding the resource and energy potential due to prospective fuel resources

Shale oil

Currently, shale oil field development is considered as cost-effective if one ton of shale contains not less than 90 liters of oil[6]. World reserves of such shale amount to 650 trillion tons, which makes 26 trillion tons of oil. This is 13 times more than mobile oil reserves. Upon shortage of energy, the cost-effectiveness threshold may be reduced to 40 l/ton [31]. According to 1980 World Energy Conference, the reserves of combustible shale that contain more than 40 l of oil in one ton is equivalent to $200 \cdot 10^{22}$, which is 8.5 times more that may be yielded from world reserves of oil, gas and coal.

The extremely rich combustible shale fields in Estonia may yield 320 l of oil products from 1 ton of raw shale. The development of the fields started in 1915. The annual yield of shale oil was 315 thousand tons. For years, oil and gas were successfully extracted from shale in the USSR and China[7]. Following the World War II, Leningrad was supplied with gas extracted from Estonian shale. Let us assume that shale oil has been being produced starting from the year 1900.

The assumed reserves of fossil hydrocarbons (traditional oil, gas, coal, and shale oil) are equivalent to $223.9 \cdot 10^{22}$ J (Table 1). Let us assume that the calorie value of shale oil is $44 \cdot 10^{6}$ J/kg, and its production before the exhaustion of the traditional fuels is equal to that in 2013, i.e. $1.1 \cdot 10^{9}$ barrels/year, which is equivalent to $6.6 \cdot 10^{18}$ J/year. Upon the assumption that shale oil will substitute for the traditional fuels after their reserves will have been exhausted and that shale oil will be produced at a rate equivalent to $1.97 \cdot 10^{20}$ J/year, the time of exhaustion of all carbohydrates determined using the algorithm defined by Eqs. (6, 7) will be 10117 years. The proportion (7) suggests that $R_0 = 36.4 \cdot 10^{12}$ RU. Upon the assumption that cost-effective oil production from shale having oil content above 40 L/ton makes 28% of world reserves, the estimate of R_0 will be $8 \cdot 10^{12}$ RU. This is 8.9 times more that the reserves of resources adopted in the World2 model. The time of exhaustion of resources according to the present scenario is 2220 years, i.e., they will be exhausted by the year 4120.

Fig.9 illustrates the realization of GSES development scenario upon the initial reserves of carbohydrate fuels amounting to $8 \cdot 10^{12}$ RU (a 800% scenario). The number of oscillation of population size increase to 15, and of the other components of GSES, to 14. With increasing time, carbohydrate reserves decrease in a piecewise-linear manner and reach a stationary regimen. Capital investment reaches maximum during the second oscillation and then goes through damped oscillations around the main trend, which correlates with the fuels trend.

Environmental pollution will reach maximums during the first oscillations because of rapid growth of capital investment and then will reduce the maximums of population size during the second and third oscillations. To prevent hunger, GSES will have to increase the share of agricultural capital investment up to 0.9 to the total capital investment. The subsequent time trajectories of agricultural capital investment share and of environmental pollution will be analogous to the behavior of “dry friction oscillators”. In the theory of oscillations, such dissipative structures are known as oscillators with perpetual “Coulomb” friction. The role of friction in the present case is played by perpetually decreasing fuel resources and closely associated capital investment, which attract GSES components to equilibrium states.

Maximum population size will reach 5.6 billion people during the first oscillation and decrease to 2 billion during the second one. The latter figure us slightly above the maximum carrying capacity of the biosphere. The subsequent time trajectory of global population size corresponds to a “system of compelling forces”. This term is used in the theory of oscillations to designate systems where a force that is applied to a component compels it from an equilibrium. The role of compelling forces is played in the present case by decreases in environmental pollution and agricultural capital investment share upon a rather high total capital investment.

Global population size during the final oscillation reaches the second high maximum (4 billion people), and the period of the oscillation is the longest (up to 500 years). These anomalies are caused by that environmental pollution and agricultural production reach stationary conditions by that time and do not limit population growth. At the same time, because of the temporal lag of birth rate, population gradually comes a to stationary flux at a level about 1.6 billion people, which is consistent with the tolerable threshold of disturbance of the biosphere.

Thermonuclear energetics

Recent advances in controlled thermonuclear synthesis make reason to consider a scenario of GSES development based on the assumption that energy potential expansion will be brought about by using the thermonuclear energy.

The first cost effective (in terms of the Lawson’s criterion, i.e. the ratio of applied and yielded energy) thermonuclear synthesis has been carried out at Institute of Plasma Physics of the Academy of Science of China using a Tokamak-type reactor EATS.[8] By 2014, the effectiveness

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[6] http://vseonefti.ru/neft/slancevaya-neft.html

[7] https://ru.wikipedia.org/wiki/Сланцевая_нефть

[8] https://ru.wikipedia.org/wiki/Управляемый_термоядерный_синтез

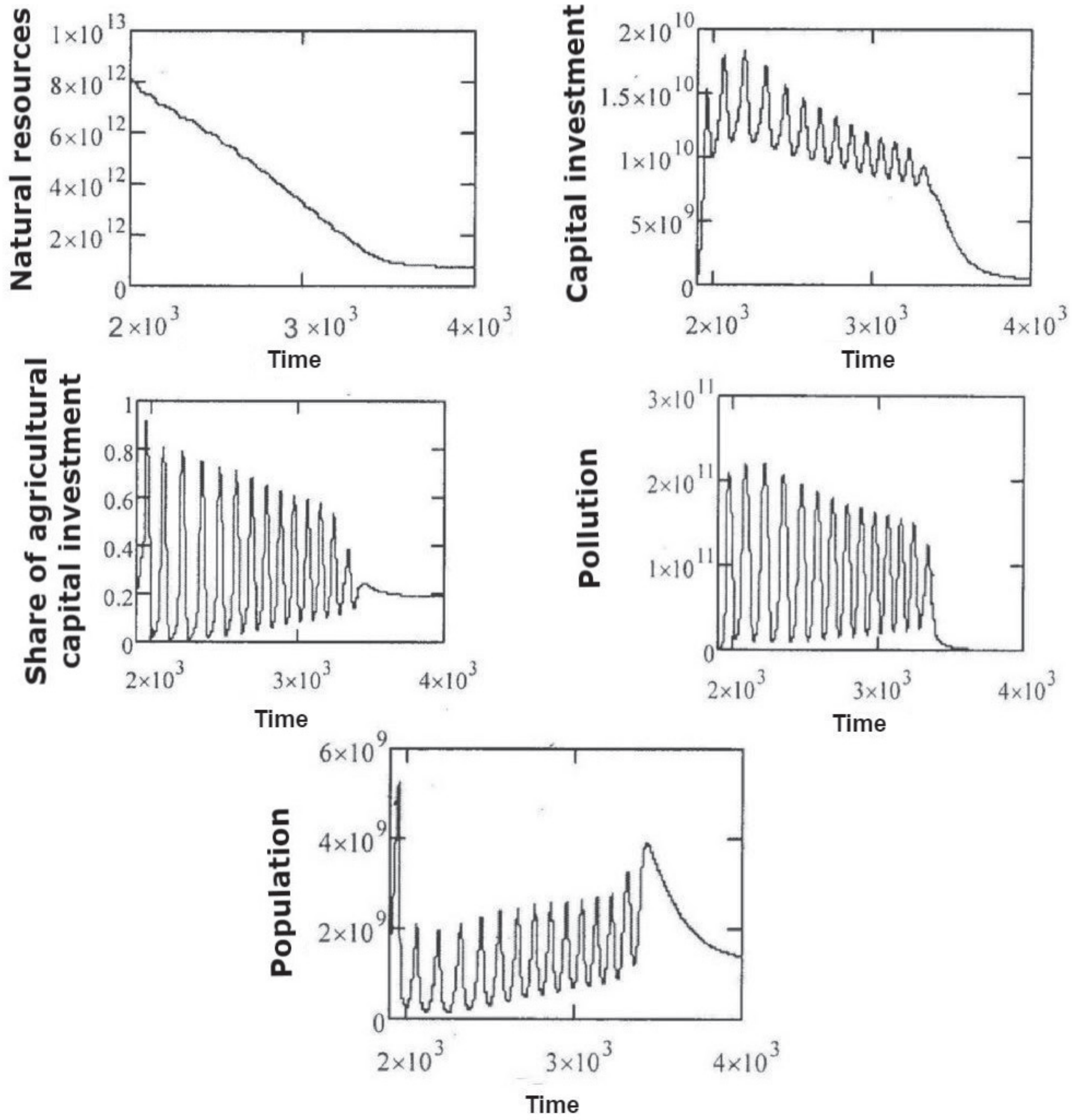

Fig. 9. Time-dependent changes in GSES components modeled with World2-MC at $R = 8 \cdot 10^{12}$ RU (the 800% scenario). See text for explanations

of synthesis reached 1/1.25, and it is planned to increase is up to 1/1.5 in near future.

It is claimed that at Max Planck Plasma Physics Institute (Germany), the experimental thermonuclear reactor “Stellator” stably produced more energy that it was applied.

The construction of the international thermonuclear reactor “ITER” is planned to be completed by 2025. The first industrial thermonuclear reactor is expected to be available in mid-XXI century.

The above makes reasons to assume that the use of thermonuclear energy in global economy will start in 2075 and that the time trajectory of its increase will be close to logistic.

Let us present the logistic model of energy availability *R* to GSES with the following equation:

$$\frac{\mathrm{d}R}{\mathrm{d}t} = (\alpha - \gamma R)R, \tag{8}$$

where: t is time and $a > 0$ and $\gamma > 0$ are the parameters of the linear dependence of r (factor of increase in available energy) on R, i.e.

$r = \alpha - \gamma R$.

Eq. 8 may be solved [25]:

$$R(t) = \frac{\alpha R_0 \mathrm{e}^{\alpha t}}{\alpha + \gamma R_0(\mathrm{e}^{\alpha t} - 1)}, \tag{9}$$

where: R_0 is available energy at $t = 0$.

Available energy has an upper limit:

$$\lim_{t \to \infty} R(t) = \alpha / \gamma. \tag{10}$$

For the numerical modeling of the scenario of expanding the resource potential due to thermonuclear energy, the model World2-MC is modified with regard to the equation related to the nonrenewable fuels. The equation adopted in World2 [32] is used for the period from 1900 to 2075, and the logistic model (Eq. 8) is used for the subsequent time. The conjunction of the right parts of the equations and of the solutions thereof is performed continuously. For this, the solution by Eq. 9 is not used, and Eq. 8 is transformed as the following:

$$\frac{\mathrm{d}R}{\mathrm{d}t} = r_0 \frac{(R_{\max} - R)}{(R_{\max} - R_0)} R, \tag{11}$$

The resulting system of fifth-order equations is solved in World2-MC using a Runge-Kutta method.

In Eq.11: $R_0 = 1.9 \cdot 10^{11}$ is the reserves of fuel resources in the year 2075, which are assumed as the initial condition in the logistic model; r_0 is the factor of increase in thermonuclear energy at t_0=2075; $R_{\max} = 21 \cdot 10^{11}$ RU is the upper limit of energy available to GSES, which is approached asymptotically by Eq.11 solution.

The derivation of the right part of Eq.11 is the same as in Section 3.3 of the present paper.

Fig. 10 illustrates the realization of the thermonuclear power scenario. Before 2075, when population size is locally stable (see Fig. 12), GSES develops by the $R_0 = 27 \cdot 10^{11}$ RU scenario. In 2075, upon the corresponding reserves of traditional fuels, the operation of industrial thermonuclear reactors begins to produce a logistic (Eq. 11) increase of energy available to GSES up to $R_{\max} = 21 \cdot 10^{11}$ RU. This level will be sustained indefinitely long. As seen in Fig. 10, all other GSES components after 2075 will experience harmonic oscillations featuring constant amplitudes relative to their stable (according to Lyapunov) stationary trends. This means that widely used thermonuclear power will be associated with an endless series of profound economic, environmental and demographic crises.

3. Alternatives to the cyclic mode of GSES development

3.1. The concept of ecological dominance of humankind in the biosphere

In taxonomic terms, the species *Homo sapiens* is referred to the kingdom of animals, and hence the ecological concept of dominance [20, p. 185] is applicable to humans as well. According to the concept, only some of numerous species included in a biocenosis determine its state because of the sizes of their populations, trophic levels, involvement in ecological metabolism or other reasons.

Humans as biosocial entities are not limited by the natural environment where they are certainly dominant. Humans have developed their own environment, which comprises, besides the natural environment, the economic, social, technological, and cultural environments. An industrial (socioeconomic) metabolism has emerged. It is poorly controlled by the society and increases with increasing production. Socioeconomic anabolism, which consumes renewable and nonrenewable natural resources, and catabolism, which results in environmental pollution, have increased to extents able to undermine the natural reserved of the planet Earth. Humankind dominates not only biota but also the whole biosphere. The force of the dominance V.I. Vernadski equates to the geological forces that formed the present-time appearance of the Earth [7]. Therefore, attempts to achieve global equilibrium by limiting the industrial metabolism are futile without correcting the power of the principal generator of the metabolism, i.e. the size of human population.

By the words of K. Ya. Kondratyev: “If humankind were able to return to limits determined by the capacity of the biosphere to bear industry, all environmental problems would have disappeared automatically, so as the anthropogenic distortions of the environment. It is, however, necessary for that to take measures aimed at a stabilization and then at the reduction of human population” [13, p. 37].

Being aware that it unfeasible in the near future to implement “the global strategy of reducing the size of human population”, K. Ya. Kondtratyev seeks solutions in the restoration of the natural communities of the biosphere: “It is necessary to reduce the areas compromised by humans from current 61% to 38%, that is by 23% or 3.2 million km^2” [13, p. 38]. These estimates are based on the assumption that the primary biological productivity of the restored areas is the same as the global mean. However, the reduction of areas distorted by the civilization will disturb the socioeconomic metabolism. Anabolic assimilation will decrease, and the decrease with result in a decrease in human population size. This problem will be considered below in more detail.

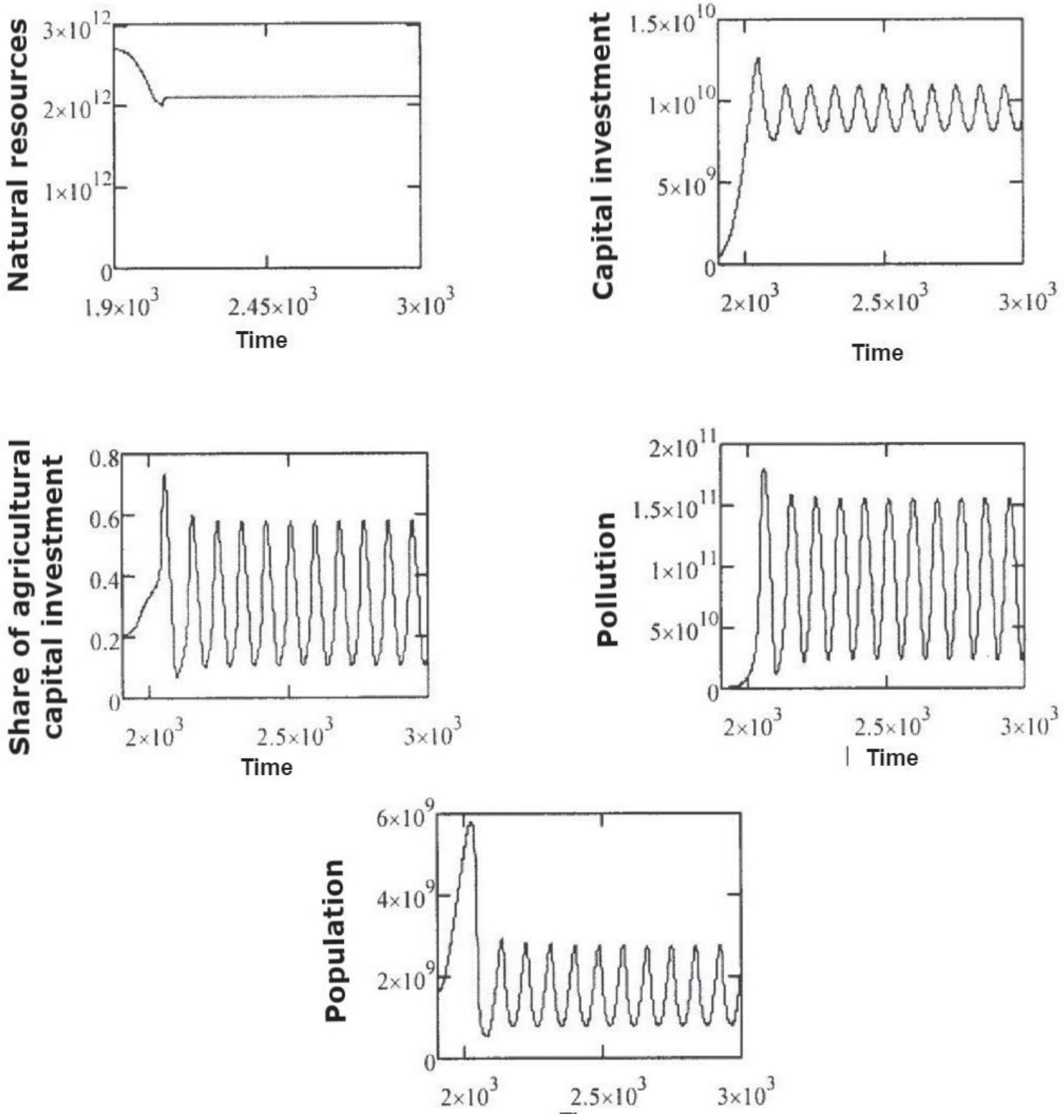

Fig. 10. Time-dependent changes in GSES components modeled with World2-MC at $R = 27 \cdot 10^{11}$ RU (the 300% scenario) until the year 2075 followed by the logistic increase of R up to $21 \cdot 10^{12}$ RU due to the use of thermonuclear energy. See text for explanations

Land reserves of GSES

The terrestrial area of the Earth is 146 · 10^6 km^2, of which 70.6 · 10^6 km^2 is suitable for life. Arable land and pasture make 15 · 10^6 and 25 · 10^6 km^2 that is 21% and 35%, respectively, of inhabitable territories.[9] The area of natural grassland and steppes is 9 · 10^6 km^2 [24]. This area should be abstracted from all pastures to estimate the area of anthropogenic interferences, which thus amounts to 16 · 10^6 km^2. On a whole, the area withdrawn from the biosphere for agriculture makes 31 · 10^6 km^2, i.e. 44% of inhabitable terrestrial areas.

The urbanized areas was 4.7 · 10^6 km^2 in 1980 and increased to 19 · 10^6 km^2, i.e. to 27% of inhabitable areas, in 2007[10].

Thus, the total area of land disturbed by GSES is 50 · 10^6 km^2, i.e. 71% of inhabitable areas. To restore the natural communities of the biosphere, the area disturbed by humans as of 2007 should be reduced from 71% to 38% (according to K.Ya. Kondratyev) that is by 33% or 23.2 · 10^6 km^2.

Restoration of the productivity of the biosphere

This is possible at the expense of areas currently used for agriculture and (or) urbanized areas. The options for that will be considered below.

1. Restoration of the productivity of the biosphere at the expense of agricultural lands

First, let us estimate the number of people sustainable with foods obtained from the current agricultural areas. At human population size equal to 6.5 billion people and at agricultural area equal to 31 · 10^6 km^2 as of 2007, the per capita agricultural area is 0.48 hectares. “Calculations suggest that to sustain each one human on the Earth with foods, 0.4 to 0.5 hectares of land is required, provided that productivity is the maximum of what is possible” [3, p. 24]. Thus, the current agricultural areas can sustain 6.5 billion people.

Upon the withdrawal of 23.2 · 10^6 km^2 from the current agricultural area, 7.7 ·10^6 km^2 will remain, and the per capita area will be 0.12 hectares, which is four times less than the above estimate. Thus, the restoration of the productivity of the biosphere due to the reduction of the agricultural area will result in a four-fold decrease in human population that is down to 1.63 billion people. Notably, this is compatible with the 1% threshold of the consumption of the primary production of the biosphere that provides for its stability (see Section 2.2.) and with the initial values of *P* in the models World2 and World2-MC for the year 1900.

2. Restoration of the productivity of the biosphere at the expense of urbanized areas

Urbanized territories area makes 38% of all areas disturbed by GSES and thus must be withdrawn completely if treated as the only reserve for the restoration of the productivity of the biosphere. In this case, 6.6 billion humans will have to return to the primitive way of life in forests and caves.

3. Restoration of the productivity of the biosphere at the expense of a partial reduction of agricultural lands.

In a scenario implying that 19 · 10^6 km^2 of the urbanized area is not withdrawn, and the current area of agricultural lands (31 · 10^6km^2) is reduced to 19 · 10^6 km^2, an area of 2 · 10^6 km^2 becomes restored. In per capita terms, this makes 0.18 hectares, which is 2.5 times below what is needed to sustain a human with food and thus is associated with a decrease in human population from 6.6 to 2.5 billion people.

The general conclusion is that restoring the productivity of the biosphere at the expense of reducing the areas currently disturbed by GSES is impossible without the concurrent decrease in the ecological dominant of the biosphere, i.e. the size of the global human population.

3.2. Local stationary points in the trajectories of the cyclic development of population size

An exit from the series of civilizational crises, which are predicted by the model World2-MC, should be sought based on the dominant role of humankind in the development of the biosphere. The equation of the demographic component of the model World2 may be written as the following:

$$\frac{\mathrm{d}P}{\mathrm{d}t} = B - D, \qquad (12)$$

where: B and D are birth and death rates (humans/year) and *P* is population.

B и *D* are defined as the following:

$$B = P \cdot C_B \cdot B_C \cdot B_F \cdot B_P \cdot B_Z, \qquad (13)$$

$$D = P \cdot C_D \cdot D_C \cdot D_F \cdot D_P \cdot D_Z, \qquad (14)$$

where: $C_B = 0.04$ (1/year) and $C_D = 0.028$ (1/year) are birth and death rates in the reference year 1970; $B_C = B_C(C)$ and $D_C = D_C(C)$, $B_F = B_F(F)$ and $D_F = D_F(F)$, $B_P = B_P(P_P)$ and $D_P = D_P(P_P)$ and $B_Z = B_Z(Z)$ and $D_Z = D_Z(Z)$ are the functions which are defined graphically (or in a tabulated format) to capture the dependencies of birth and death rates on living standards *C*, nutrition *F*, population density *Pp*, and environmental pollution *Z*. In the reference year 1970, these functions are equal to unity and do not influence the rates of birth and death. When living conditions become worse or better, the functions become, respectively, smaller of greater than unity. The arguments of these functions depend on the conditions of the components of the model.

With account for the above, Eqs. 13 and 14 may be generalized:

$$B = b(R, R, X, Z)P, \qquad (15)$$

$$D = d(R, K, X, Z)P, \qquad (16)$$

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[9] http://www.activestudy.info/zemelnye-resursy/

[10] https://ru-ecology.info/term/12651/

This open access translation of the original Russian paper published earlier shall be cited as Sergeev YuN, Kulesh VP.
Cyclic and stationary modes of the development of civilization in global models
Biosfera. 2017;9:13-47. DOI: 10.24855/biosfera.v9i1.322

where: b and d are birth and death coefficients; however:

$$B - D = E, \tag{17}$$

where: E is the rate of population size increase.

It is obvious that:

$$E = \varepsilon(R, K, X, Z)P\,, \tag{18}$$

where: ε is the coefficient of population size increase.

With account for Eqs. 17 and 18, Eq. 12 may be parameterized as the following:

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \varepsilon(R, K, X, Z)P\,, \tag{19}$$

or

$$\frac{1}{P}\frac{\mathrm{d}P}{\mathrm{d}t} = \varepsilon(R, K, X, Z)\,. \tag{20}$$

Recall that in the system of World2-MC equations, all variables are functions of time. The left part of Eq. 20, i.e. *1/P*(d*p*/d*t*), which is identically equal to $\varepsilon(R, K, X, Z)$, allows constructing a phase trajectory using the parametric form $[\varepsilon(t), P(t)]$, where time is the parameter. The same trajectory may be constructed as a set of points in a $\{1/P(t)\,[\mathrm{d}P(t)/\mathrm{d}t], P(t)\}$ plane. Fig. 11 shows the plane trajectory for the 300% scenario upon the initial reserves of fuel resources $R_0 = 27 \cdot 10^{11}$RU.

In population ecology, the spiral phase trajectory in Fig. 11 is called the Olley curve. It is typical of populations featuring expressed altruistic behavior of their members, such as collective protection from predating, joint care for progeny etc. [25]. Olley curve appears to be featured by humankind too.

Spline approximation of an Olley-type trajectory makes it possible to solve Eq. 19 numerically. This solution is approximated by the behavior of $P(t)$ in World2-MC.

A stationary trajectory of a global model is the limit to which it approaches. A specific case of stationary trajectory is an implicit equilibrium where all rates defined by differential equations of a model turn to zero. Considering an equilibrium as global is possible only if there exists a point in the phase space of all components where all of the right parts of equations in a model turn to zero upon $t \to \infty$.

Let us denote local stationary points with the superscript$^{(c)}$. The local stationary points $P^{(c)}$ of Eq. 19 are defined by dP/dt = 0. In an Olley-type trajectory, several local stationary points are possible. There are six such points in the $R_0 = 27 \cdot 10^{11}$ scenario (300%). The stability or instability of these points is defined by the sign of the derivative $\frac{\mathrm{d}}{\mathrm{d}P}[\varepsilon(P)P]$ at the stationary point $P^{(c)}$ [25].

The derivative may be expressed as the following:

$$\varepsilon(P)P] = P\frac{\mathrm{d}\varepsilon(P)}{\mathrm{d}P} + \varepsilon(P)\frac{\mathrm{d}P}{\mathrm{d}P} = P\frac{\mathrm{d}\varepsilon(P)}{\mathrm{d}P} + \varepsilon(P)\ . \tag{21}$$

With account for Eq. (20), it may be written:

$$\frac{\mathrm{d}}{\mathrm{d}P}[\varepsilon(P)P] = P\frac{\mathrm{d}\varepsilon(P)}{\mathrm{d}P} + \frac{1}{P}\frac{\mathrm{d}P}{\mathrm{d}t}\,. \tag{22}$$

However, dP/dt is 0 by definition at a stationary point. Therefore, Eq. 22 may be replaced with the following:

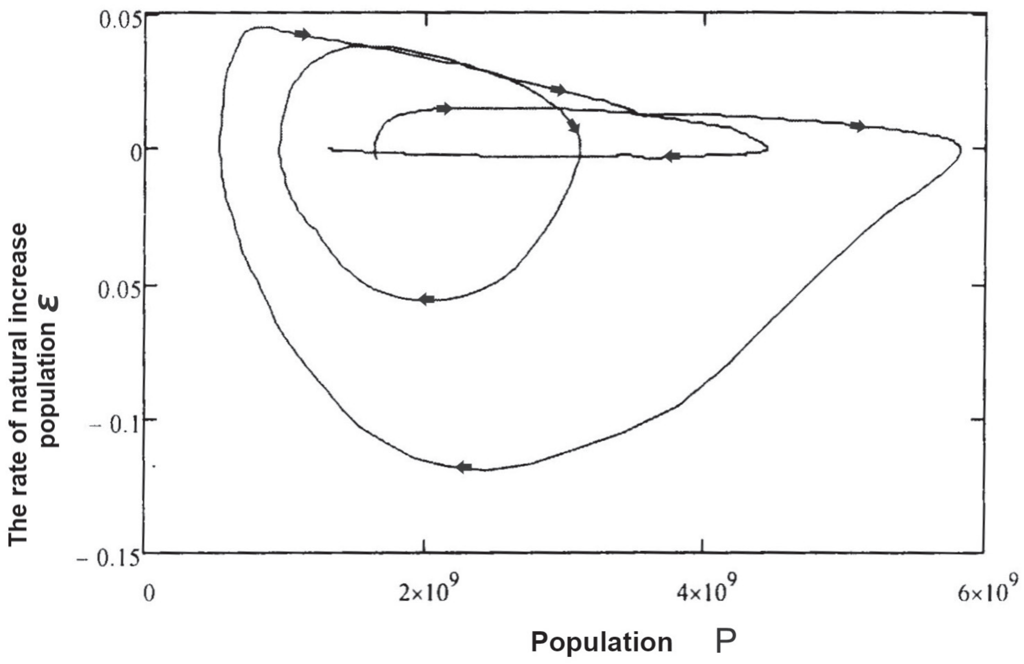

Fig. 11. Olley-type plots for World2-MC population size at $R_0 = 27 \cdot 10^{11}$ RU (the 300% scenario)

$$\frac{\mathrm{d}}{\mathrm{d}P}[\varepsilon(P)P] = P\frac{\mathrm{d}\varepsilon(P)}{\mathrm{d}P}. \qquad (23)$$

A local stationary point is stable if $\mathrm{d}\varepsilon(P)/\mathrm{d}P < 0$ at this point and is unstable if $\mathrm{d}\varepsilon(P)/\mathrm{d}P \geq 0$. The sigh of a derivative is defined by the tangent of $\varepsilon(P)$. It is seen in Fig. 12 that the $R_0 = 27 \cdot 10^{11}$ RU scenario features two stable $P^{(cs)}$ and three unstable $P^{(cu)}$ stationary points and a trend, which shows Lyapunov's stability and approaches the limit density P^*. In the present case, P^* is 1.3 billion people.

With any nonzero values of P, a population will tend to local stationary states. A population will tend to a stationary state $P_1^{(cs)}$ at $P \in (P_0, P_1^{(cu)})$; to $P_1^{(cs)}$ at $P \in (P_1^{(cu)}, P_2^{(cu)})$; and to P^*at $P \in (P_3^{(cu)}, \infty)$ (Fig. 12). Clearly, the local stationary state $P_1^{(cs)}$ is the optimal P_0 in a scenario implying an accelerated transition from cyclic to stationary GSES trajectory.

3.3. Accelerated transition from cyclic to stationary time trajectory of GSES

On Jan. 1, 2016, the population of the People's Republic of China reached 1.378 billion people, the annual increment being 7.28 млн[11], despite economic measures (one family, one child) taken to reduce birth rate. This is far above stationary values suggested by World2-MC. By the same date, the population of India reached 1.252 billion people[12]. In 1994, a UN Conference on Population and Development was held in Cairo[13]. The conference has shown that corporative, national and confessional egoism dominates over universal interests. Global population has increased by 1.622 billion since those times and achieved 7.296 billion on Jan. 1, 2016[14]. Global economic crises and numerous local wars in a unipolar World distract enormous resources from solving global problems. This being true, only overt social optimists may believe that everything will be all right be default. The right time for reforming the world system has been already missed. The first oscillation of global population is most likely inevitable.

The second and the third oscillations of the global population may be prevented if after the demographic crisis of the XXI century the global population will be controlled according to the logistic model:

$$\frac{dP}{dt} = (\alpha - \gamma P)P. \qquad (24)$$

where: $\varepsilon = \alpha - \gamma P$ is the coefficient of increase in population P; and $a > 0$ *and* $\gamma > 0$ are the parameters of the linear dependence of the coefficient ε on P.

Population cannot increase infinitely. Its size has an upper limit:

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[11] countrymeters.info/ru/China

[12] countrymeters.info/ru/India

[13] https://www.unfpa.org/sites/default/files/event-pdf/icpd_rus.pdf

[14] https://ru.wikipedia.org/wiki/население_Земли

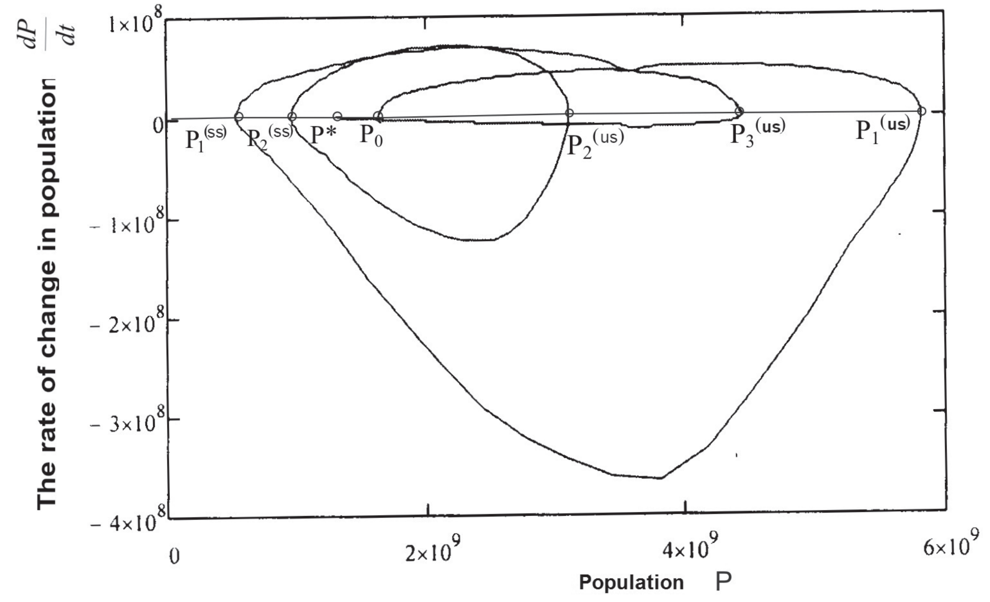

Fig. 12. Phase diagram of the model d*P*/d*t* = ε(*R, K, X, Z*)*P upon the starting traditional fuel reserve* $R_0 = 27 \cdot 10^{11}$. P_0 – trivial stable state; $P_1^{(us)}$, $P_2^{(us)}$ – locally stable stationary states; $P_1^{(ss)}$, $P_2^{(ss)}$, $P_3^{(ss)}$ – *locally unstable stationary states;* P^* – limiting population density

$$\lim_{t \to \infty} P(t) = \alpha/\gamma = P_{\max} \quad , \qquad (25)$$

where: $P_{\max}$ is the limit approached by P asymptotically. Eq. 24 may be rewritten as:

$$\frac{dP}{dt} = \frac{1}{\gamma}\left(\frac{\alpha}{\gamma} - P\right)P \, , \qquad (26)$$

or, with account for Eq. 25, as:

$$\frac{dP}{dt} = \frac{1}{\gamma}(P_{\max} - P)P \, . \qquad (27)$$

where *g* is an independent parameter.

The parameter γ may be expressed with other constants, P_0 and ε_0, which are population size and the coefficient of its increase, respectively, at time t_0. Clearly, $\varepsilon_0 = \varepsilon_0(P_0)$. Let us assume that:

$$\frac{1}{\gamma} = \frac{\varepsilon_0}{P_{\max} - P_0} \, . \qquad (28)$$

Putting Eq. 28 in Eq. 27 will yield the following:

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \varepsilon_0 \frac{(P_{\max} - P)}{(P_{\max} - P_0)} P \, . \qquad (29)$$

Eq. 29 is equivalent to Eq.24. Obviously, the linear dependence of the coefficient of population increase on population size is defined as

$$\varepsilon = \varepsilon_0 \frac{(P_{\max} - P)}{(P_{\max} - P_0)} \, . \qquad (30)$$

An accelerated transition from cyclic to stationary GSES development may be exemplified with the $R_0 = 27 \cdot 10^{11}$ RU (300%) scenario, which is the most likely one. According to it, the first local stationary state must be achieved in 2075 at P_1(cs) = 0.54 billion people (Fig. 12). This size may be assumed as the initial condition $P_0 = 0.54$ of the logistic model. Let us assume that is 0.02 in 2075 and that Pmax is $P^* = 1.5$ billion people, i.e. corresponds to the stationary, according to Lyapunov, trend of population size.

Fig. 13 illustrates an accelerated transition of GSES to a displaying a stationary Lyapunov's trend in time. It is seen that, at $\varepsilon = 0.02$, population becomes stationary approximately in 160 years, that is by 2240. The transition may be delayed or accelerated by varying the parameter ε_0.

To explain the temporal variability of GSES components in the present scenario, historical examples and the flux diagrams that show feedbacks in the model World2 [32] will be used below.

After the end of the first demographic crisis, global population size will fall to 0.54 billion people. This is similar to what had been achieved in mid-XVII century [23]. In those times, water wheels and windmills were used as engines. Population reached 1.5 billion in late XIX century when steam was mainly used in engines and wood was used as the main fuel. Humankind existed in those times due to the renewable resources. Now let as have a look into the future. The logistic growth of population will result in 1.5 billion people, and this population size will be constant during subsequent centuries. Population will be in a stationary flux sustained mainly due to the renewable natural resources. The nonrenewable natural resources will be virtually unneeded after 2075 and will be in a stationary flux at a levels of $19 \cdot 10^{11}$ RU.

According to World2 flow charts, the economic capital investment (the capital investment of industry, services, and agriculture) depend on population size (the number of investors) and living standards, which depend in their turn on the current reserves of fuel resources. The capital investment ($1.3 \cdot 10^{10}$ capital units, CU) built up during the ascending phase of GSES development in 1900–2022 due to the investors that have sufficiently high living standards (5.82 billion people) feature a considerable lifetime of about 40 years and the corresponding temporal lag of their development. In the descending phase of population size changes in the years 2022 to 2075, this lag maintains the basic asserts at a level of about $7.5 \cdot 10^9$ CU. In the phase of the logistic growth of the global population (the number of investors by inference), the capital investments increase up to 10^{10} CU and enter, following the size of the population, a stationary phase.

The share of the agricultural capital investment among the entire economic capital investment is determined primarily by the nutritional conditions of population and by the lifetime of the agricultural capital investment. During the phase of population increase, the share of the agricultural capital investment increases up to 0.75 of the entire economic capital investment. A small temporal lag of agricultural capital investment (15 years) does not present their degradation during the phase of population decrease. By 2075, their share must decrease down to 0.06. During the phase of the logistic grown of population, the share of the agricultural capital investment must increase up to 0.9 and reach its stationary level.

Environmental pollution depends on the rates of pollutants generation and destruction. Generation rate is a function of population size and *per capita* capital investment. Destruction rate depends of the level of pollution and the rate of environmental self-cleansing. During the phase of increases in population and capital investment, pollution increases up to $1.7 \cdot 10^{11}$ pollution units (PU). During the phase of decreases in these components of GSES, pollution decreases due to a decrease in the generation and an increase in the destruction of pollutants. During the logistic phase of capital investment increase, pollution increases up to $2.5 \cdot 10^{11}$ PU and reaches its stationary level.

It may seem that stationarity returns GSES back to the XIX century. To see that this is not so, it suffices to compare the initial conditions of GSES components with their levels upon reaching stationarity. Clearly, basic asserts increase so as the material component of living standards does. The nutritional component becomes increased too. Indeed, the agricultural capital investment, which is defined as the total capital investment multiplied by the share of the agricultural capital investment, was $0.08 \cdot 10^9$ CU in the year 1900 and must be $0.9 \cdot 10^9$ CU in 2500.

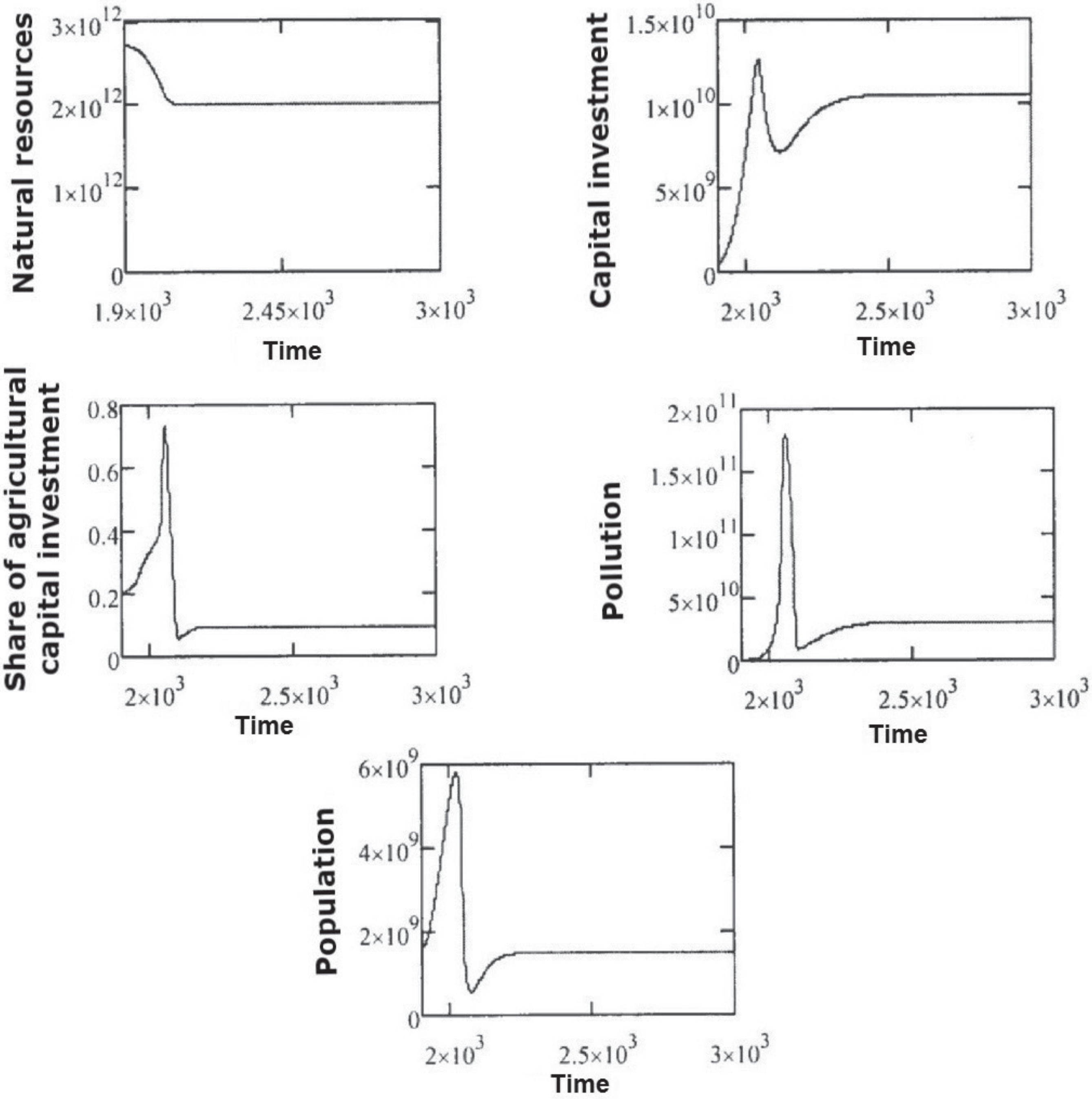

Fig. 13. Time-dependent changes in GSES components modeled with World2-MC at $R = 27 \cdot 10^{11}$ RU (the 300% scenario) until the year 2075 followed by the logistic increase in P at $\varepsilon = 0.02$ и $P^{*} = 1{,}5$ billion people. See text for explanations

4. GSES development cycles are associated with the developmental phases of the global hyper-ethnos: a hypothesis

A smooth transition of global population to stationarity is possible, by all appearances, only upon the formation of a global hyper-ethnic system based on a common mentality of population, that is on mental features and outlooks shared by all people. This assertion will be considered in more detail below.

The formation of a global hyper-ethnos is taking place already because of globalization. The postindustrial era that have come to existence at the turn of the XX and XXI centuries is characterized by the explosive development of transnational corporations and common market, which transforms global economy into an international enterprise. The natural landscapes, which accommodate ethnoses, become increasingly degraded. Information technologies are developing to an unprecedented scale. The world-wide web, telecommunication networks, and satellite TV are forming a unified informational medium. The mass culture is ousting the classic and folk cultures. Education is adopting international standards based on intergovernmental treaties, and languages are increasingly being adopted to the English language, which has become a means of international communication. International logistics is rapidly developing. Humankind is being stratified to form, in particular, a hunger belt along the equator through Africa, Middle East, South-East Asia, and Latin America where up to 30% of people are starving [14]. These inequalities in socioeconomic development drive planned and spontaneous labor migration, which results in ethnic mixing. All these factors promote the development of a unified mentality and the formation of a global hyper-ethnic system, which may be able to control birth rate upon the transition of the global population to the logistic mode of growth.

In [30], the development of North-American, Western European, Chinese, Islamic, and Eurasian super-ethnoses was considered. It was concluded that the most likely core for the formation of a global hyper-ethnos is the North-American super-ethnos because it is the youngest and the most dynamic and "passionate" (in the Gumilev's[15] sense of the word) of all super-ethnoses.

The below discussion will be based on the assumption that a global hyper-ethnos is developing already in the course of globalization based on the core comprised of the North-American and West-European super-ethnoses, which are highly "passionate" and similar to each other in the basics of their mentalities. This is the most likely scenario as of today. Among the three World2-MC scenarios of GSES development, the scenario to consider implies 300% greater reserves of nonrenewable resources than it is assumed in the Wold2 model. With account for the fact that resources are increasingly consumed and the cost of their production is increasing with time, this scenario seems to be the likeliest. A three-fold increase in reserves is equivalent to $R_0 = 2700 \cdot 10^9$ (starting from the year 1900, the reserves are sufficient for 750 years, the rate of the consumption of the resources being the same as in 1970). The initial conditions for all other model components are assumed in this scenario to be same as in the basic World2 variant: $P_0 = 1.65 \cdot 109$ people (global population), $K_0 = 0.4 \cdot 10^9$ CU (global capital investments; it is assumed that per capita capital investment in 1990 was four times less than in 1970); $X_0 = 0.2$ (the share of the agricultural capital investment); and $Z_0 = 0.2 \cdot 10^9$ PU (environmental pollution; it assumed that per capita pollution in 1990 was eight time lower than in 1970). The results of modeling of GSES development under these conditions is illustrated in Fig. 14.

The abscissa in Fig. 14 shows the timescale, which ranges from 1900 to 2800, and the phases of ethnogeny. The ordinate scale is the same for all components. Figure captions indicate the names and graphic identifies of the components and the divisors for dividing the values of components derived from the respective plots in order to obtain the actual values.

Modeling results suggest that the oscillations of GSES components qualitatively correspond to the phases of ethnogeny discovered by L.N. Gumilev in his studies of human history. This makes it possible to consider jointly the ethnic and the socio-ecological aspects of the development of civilization.

The ascending phase of hyper-ethnos

This phase comprises to stages: the latent and the manifest ascent. The latent ascent may be assumed to start in the early XVIII century, the time of increasing migration of "passionaries" from Europe to North America and the onsets of the industrial era (pre-monopolistic capital investmentism) and the demographic explosion (in 1650, global population amounted to but 550 million people [23]). This stage, according to L.N. Gumilev's estimate, lasted for 150–200 years. Thus, the manifest stage of the ascending phase began in the early XX century.

During the manifest stage of the ascending phase, the passionarity of an ethnic system drastically increases. The bearers of passinonarity consolidate within the field of their action the masses of ordinary personalities. This time is distinguished by highly expressed manifestations of all types of activities within a hyper-ethnos: demographic explosion, economic growth, environmental problems, inner conflicts, rapid proliferation of ethnic subsystems, and the emergence of highly disciplined ethnic collectives.

An exponential growth of a population is associated with a similar increase in the number of "passionaries". Because of their high fertility, their number may increase even faster than the number of ordinary people does.

Another evidence of an increased passionary intension is the breakdown of the colonial system after World War II. Former colonies became independent states thus making the complexity of the global hyper-system to increase. An international ruling body that emerged is the United Nations.

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[15] http://discovery.ucl.ac.uk/1446515/1/U602440.pdf

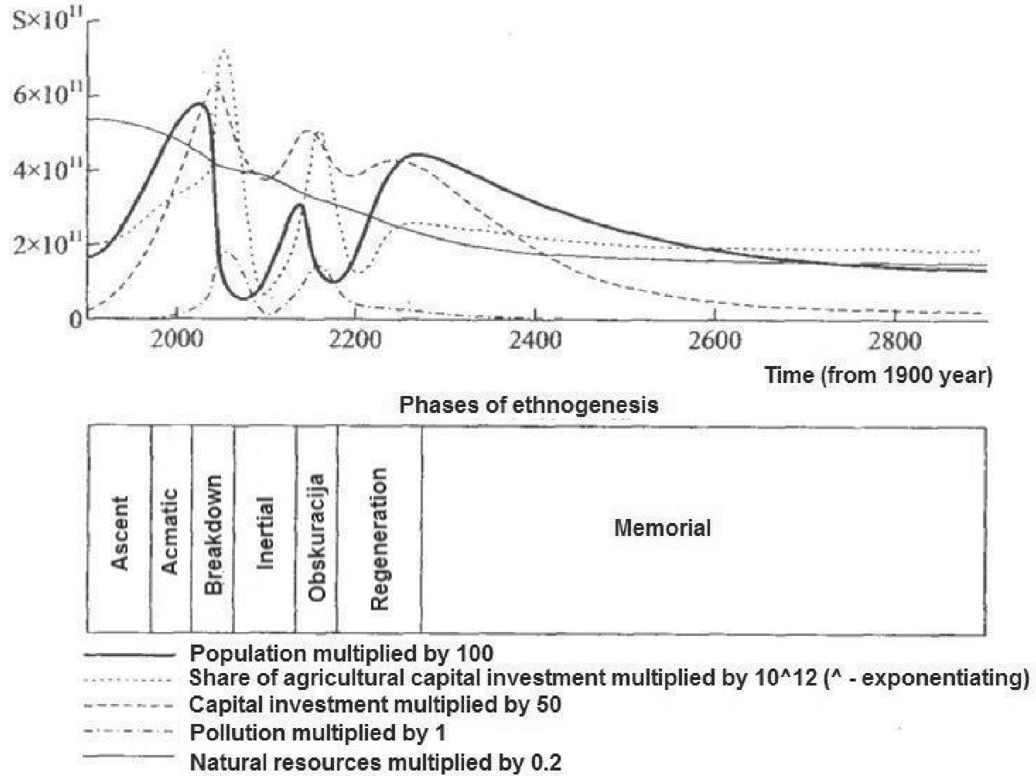

Рис. 14. Time-dependent changes in GSES components and the phases of a global hyper-ethnos development. See text for explanations

Increased activities of the economic agents of the hyper-ethnos at the manifest stage of its ascent are expressed in the transition from the pre-monopolistic to monopolistic capital investmentism, the emergence of transnational companies, and the explosive growth of the gross domestic and gross national products. The driving force of the market economy are businessmen, who are usually excessively energetic and striving for maximal gains at minimal expenses.

According to World2-MC, the capital investment of global economy increased from $0.44 \cdot 10^9$ CU in 1900 to $0.65 \cdot 10^9$ CU in 1990, that is 15.6 times. Population growth made it necessary to increase the share of the agricultural capital investment from 0.2 in 1990 to 0.32 in 1990. Environmental pollution gradually increased. The reserves of the nonrenewable natural resources decreased from $27 \cdot 10^{11}$ до $24 \cdot 10^{11}$ RU. Thus, only 10.8% of the initial reserves were spent during the manifest stage of the ascending phase of the development of the hyper-ethnos.

The acmatic phase of hyper-ethnos

The acmatic phase, according to L.N. Gumilev, is a fluctuation of the passionary intension that occurs at the ultimate level of passionarity following the ascending phase. The time when the ascending phase ends may be determined by changes in the type of relationship between the coefficient of population increase and population size: a positive correlation is replaced by a negative one. Formally, this corresponds to the bending point of population growth curve, where $(d^2P(t)) / (dt^2) = 0$. Upon a discrete representation with 1-year intervals, the bending point is determined by the equation $P_{i+1} - 2P_i + P_{i-1} = 0$. World2-MC suggests that the acmatic phase started in 1990. According to demographic statistics, global population size was 5 billion people in 1987, 6 billion on 2000, and 7 billion in 2012. Thus, the increase in global population was stabilized, in conformance with modeling results.

During the acmatic phase, passionaries develop a desire for maximal personal self-assertion even if the desire contradicts the interests of one's native ethnos. A recent example of such self-assertion may be found in the history of USSR breakdown, when the political leaders of Russia, Ukraine, and Belorussia at their meeting in Belovezhskaya Forest signed the treaty stipulating that their republics will come out of the USSR in spite of the results of general referendums in these republics. As a result, 15 new states have emerged in the former USSR territory.

Inflated individualism associated with increased passionary intension brings the hyper-ethnos to an "overheated" state. In this state, excessive passionarity is spent in interethnic conflicts, which may be exemplified with the sovereignty parades of FSU countries, Nagorno-Karabakh conflict, armed conflicts between Georgia and Abkhazia and South Ossetia, wars between former republics of Yugoslavia etc. During the acmatic phase, the number of ethnic subsystems and the frequency of significant events in ethnic history are maximum. The phase is not ended yet, and much may happen during the rest of its time.

According to World2-MC modeling, population must increase from 4.82 billion people in 1990 to 5.81 billion in 2022 during the acmatic phase. However, population growth rate must gradually decrease to zero. The capital investment of global economy continue to grow stably from $0.6565 \cdot 10^{10}$ CU in 1990 to $1.1 \cdot 10^{10}$ CU in 2022, that must increase 1.7 times. The continuing population growth requires further expansion of agriculture. The share of the agricultural capital investment during the acmatic phase must increase from 0.32 to 0.37. Environmental pollution also continues to increase. The reserves of the nonrenewable resources must decrease from $24.1 \cdot 10^{11}$ to $21.9 \cdot 10^{11}$ RU during 32 years.

The breakdown phase of hyper-ethnos

According to L.N. Gumilev, the breakdown phase is associated with a dramatic decrease in population size. The number of passionaries decreases proportionally. The passionary intention in an ethnic system decreases deeply. This is associated with ethnic field fracture, acute conflicts, and increasing number of indifferent people. The indifference is expressed in inability to control instinctive lusts and in asocial behavioral traits, parasitism, and insufficient care for progeny. Such people usually concentrate in cities and are responsible for increasing alcoholism, drug addiction, and criminality.

World2-MC modeling suggests that the time of transition from the acmatic to the breakdown phase is determined by the time of reaching the first maximum of population size. This must occur in 2022. During the next 55 years, global population will decrease from 5.81 billion people to 0.54 billion because of extremely low birth rates. This is nothing else but a profound demographic crisis.

For living standards improvement and demographic crisis prevention during the breakdown phase, global capital investment must increase from $1.1 \cdot 10^{10}$ CU in 2022 to $1.26 \cdot 10^{10}$ in 2040. The share of the agricultural capital investment must increase drastically, from 0.37 in 2022 to 0.72 in 2040. The intensification of economic development will result in a catastrophically increased environmental pollution, which must reach $1.8 \cdot 10^{11}$ PU by 2054. This is 1000 time more than in the year 1990.

The economic measures will not stop the depopulation process. Labor force deficit will lead to economic recession and then to stagnation. By the end of the breakdown phase, world capital investment will decrease to $0.88 \cdot 10^{10}$ CU, that is to 30% of the maximum. The share of the agricultural capital investment will decrease to 0.36, that is will two times less than its maximum.

The inertial phase

During the phase named by L.N. Gumilev as inertial, population grows again. Because of the genetic drift, the number of passionaries increases. A characteristic feature of this phase is the consolidation of governmental power and social institutes. Material and cultural treasures accumulate. Environmental landscape are actively transformed. The predominant personality traits are loyalty and workability. Labor is perceived as not a burden but a valuable prerequisite of wealth. Enormous useful work is carried out.

It is tempting to supplement this characteristic of the inertial phase according to L.N. Gumilev's analysis of the past with what follows from V.V. Olenyev's and M.P. Fedorov glimpse into the future: "The task of developing a controlled world may be fulfilled only based on a controlled and planned socioeconomic system, such as 'ecological socialism'" [21]. In L.N. Gumilev's theory of ethnogeny, one of the main factors that determine the development of an ethnos is the development of the productive forces, which transforms productive relations and, hence, social organization. It follows from the law of conformance of productive relations to productive forces and the law of decreasing potential of natural resources that the "environmental-social-economic development (of a socio-environmental system) corresponds to the formula [24]: (potential of natural resources) ↔ (productive forces) ↔ (productive relations).

When economic growth discontinues (deep depression during the breakdown phase), market economy becomes needless. The capital investmentistic mode of production, which is based on achieving maximum gains at minimum expenses, most often operates at the expense of destruction of the biosphere and thus is dangerous for the humankind.

Modeling suggests that the time of the end of the breakdown phase and of the beginning of the inertial phase is determined by the date of achieving of the first minimum of population size (the year 2075, 0.54 billion people). In the subsequent years, population will increase due to a decrease in death rate and an increase in birth rate. The capital investment will increase again after their short-term decrease to $7.52 \cdot 10^{9}$ CU in 2097. The share of the agricultural capital investment increases again after its drastic reduction to 0.07 in 2095. Environmental pollution decreases to $1.22 \cdot 10^{10}$ PU in 2097 and starts to gradually increase again.

If the hypothesis that ethnogeny phases are associated with GSES cycles is true, then the transition to the logistic growth of population size is possible without economic, social and environmental cataclysms. The negative experience of the breakdown phase and the transition of dominant personality traits from sub-passionary to harmonized in the inertial phase will facilitate birth control ensuring the maintenance of a current population size.

Conclusions

The World2-MC scenarios of global development lead to conclusions, which, although do not forecast the development of GSES, still point at significant trends:

1. In the XXI century, the humankind will experience not a catastrophe forecasted by Wold2 and World3 models, but rather a series of profound crises followed by recovery. Less profound regional crises having other origins have been experienced by the humankind not once in the past.
2. The global socio-environmental system (GSES) has the potential to develop in a cyclic manner during the third millennium. The number of cycles must increase proportionally to energy availability for humankind. Each cycle ends with a crisis. When the resource and energy potential is limited by the traditional fossil fuels reserves (oil, gas, and coal), three to four cycles may be expected. Upon expanding the potential due to shale oil, there may be up to 15 cycles followed by stationary (in Lyapunov's sense) developmental trends of GSES components.
3. Upon widely used controlled thermonuclear synthesis, the number of cycles must increase infinitely, and GSES must enter a harmonic oscillator regimen and thus experience fluctuations around an equilibrium state.
4. The humankind is the ecological dominant of the biosphere within each separate cycle of GSES development. Capital investment, food, and environmental pollution, which are the products of the socioeconomic metabolism of the humankind and depend on the current reserves of energy resources, limit human population size within a cycle but do not determine the number of cycles.
5. In the five model scenarios, which differ in their initial reserves of fuel resources, the stationary levels of population size reached by GSES after its final cycle range from 1.3 to 1.6 billion people. Population size that corresponds to a 1% threshold of primary product consumption, which provides for the stability of the biosphere, amounts to 1.7 billion people. A similar calculated population size (1.63 billion people) is sustainable by the biosphere in the scenario that implies the complete recovery of the present-time agricultural lands. Thus, the threshold population size, to which the logistic curve of population size approaches asymptotically, ranges from 1.3 to 1.7 billion people.
6. Computations suggests that the restoration of the ecological systems that are currently substituted with agricultural lands and urbanize territories, which is proposed in the biospheric concept of sustainable development as an alternative to the reduction of human population size, is unfeasible without the proportional and simultaneous reduction of the latter. Means to restore ecosystems are discussed in the biospheric concept, whereas means to reduce human populations are ignored.
7. The cyclic trajectory of changes in global population is a manifestation of the spiral shape of the curve that reflects the dependency of the coefficient population growth on population size. In population ecology, this is known as Olley curve. The curve explains the existence of several stable and unstable local stationary states of the cyclic development of population. The stable states provide for the possibility of an accelerated transition of GSES to stationarity.
8. GSES may transit from the cyclic to the stationary mode of its development starting from a stable local stationary state via the logistic growth of population size, its saturating size being 1.5 billion people.
9. A smooth transition is possible, by all appearances, only after the formation of a global hyper-ethnic system featuring a common mentality, i.e. common mental traits and general outlooks, of all people in a controlled and planned socioeconomic system of an "ecological socialism" type.

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