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Biophysical sustainability of land use systems

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ABSTRACT

The "sufficiency" of land unit properties can be gauged by monitoring selected system parameters and matching these with values calculated for a rigidly defined "production situation". Land use system analysis must account for the dynamics of the system. The complexity of actual land use systems defies dynamic analysis. "Simplified" systems, in which limitations such as nutrient deficiencies, weeds infestation, pests/diseases, harvest losses and "Acts of God" are assumed remedied through appropriate management activities, can be handled but the calculated plant (organ) masses reflect potential rather than actual system performance. They may be valuable nonetheless: defining land units in terms of their most "relevant" land qualities ensures that much of the variation in the performance of actual land use systems is found back in the analyses of simplified systems that have a reference function. Analyzing the "yield gap" between calculated reference and observed actual systems performance, with maximum use of geo-information to facilitate regionalization from point analyses to an analysis of land, is a way to examine the sustainability of actual land use systems. The approach is now being examined in cooperative research projects in China and Zimbabwe.

LAND USE SYSTEMS

In its simplest form, a land use system is composed of one land utilization type practised on one land unit. Such "single" land use systems are core elements in land suitability assessment; procedures have been worked out to quantify crop performance in simple land use systems with uniform fields that are planted to pure stands of annual food or fibre crops. More complex forms of land use can be handled as aggregations of single land use systems: rotations are sequences of single land use systems, and intercropping can in theory (sic!) be analyzed by examining concurrent single land use systems that share the same land unit, provided that one accounts for the mutual competition for light, water and nutrients of the two systems.

In the present context, a land use system is considered "biophysically sustainable" if the compounded sufficiency of relevant land attributes does not deteriorate under the applied land use, and that against a realistic time horizon. Sustainability is an equilibrium problem. Crop growth modelling and monitoring of relevant "land quality indicators" [2] are the means to judge:

(1) the sufficiency of the system's supply side—defined in terms of land management attributes—in the face of the compounded land use requirements (*ie*, the demand side)

(2) the sustainability of the system over the years.

Comparing calculated (reference) crop production potentials with observed crop performance offers interesting prospects for early warning applications and crop yield forecasting.

DYNAMIC LAND USE SYSTEM ANALYSIS

Land use systems are dynamic systems; the specifications of both the land unit and the land utilization type change over time. Modern crop growth models account for the dynamic nature of land use systems by applying a procedure of numerical integration over time: calculations of crop growth and development are done for a succession of short time intervals in the growing cycle of the crop. Dependent "state" variables signify the state of the system during a particular interval. (Interval lengths are normally 1 day: a trade-off between the requirements of system dynamics and the availability of primary data.)

The sequence of intervals starts with the moment of crop emergence or planting. The calculations for the first interval in the growing cycle start with known values of all state variables. Interval-specific values of exogenous "forcing" variables (*eg*, weather data and management specifications) are called, after which processes that take place are calculated assuming steady state conditions for the duration of the interval. All state variable values are updated at the conclusion of each set of interval calculations; their new values reflect the state of the system in the next interval when new interval-specific forcing variable values are called and calculations of changes in state variable values are repeated. The sequence of interval calculations ceases when (the interval of) physiologic crop maturity is reached or growth has become impossible because of lethal temperature or water conditions.

This "state variable approach" befits the dynamic nature of land use systems but is prone to the rapid propagation of errors imported with the (frequently called) primary data and incurred in the calculations of such essential processes as assimilation, maintenance respiration and growth respiration. The procedure followed is "transportable" provided that only universally valid chemical, physical and biologic laws are used in the algorithm and empirical (observed cause-effect) relationships are avoided. Ideally, the interpretation procedure would be entirely time- and site-independent, and local effects would be brought in exclusively by time- and site-specific input data such as weather data and management specifications.

State variable values such as the dry leaf mass or total plant mass per ha are calculated for any interval (day) in the growing cycle of a crop and are strictly system-specific. In theory, they could be used as gauges of the

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compounded "sufficiency" of all land qualities that define the land unit in the system (*ie*, the "supply side"). One would simply compare them with values calculated for a hypothetic system with similar specifications but with correctable limitations removed. Calculating such sufficiency values for a sequence of years would reveal the long-term biophysical sustainability of a particular land use system. This sounds too good to be true. It is too good to be true!

WE SMPLFY

Real-world farming involves land use systems of considerable complexity. The "demand side" is composed of a wide variety of "land use requirements", such as "adequate light and temperature conditions", "adequate water supply", "adequate nutrient supply", "adequate weeding", "adequate control of pests and diseases", etc. Many of these requirements are too complex to be modelled. Consider, for example, the land use requirement "adequate supply of plant nutrients", or—simpler—"adequate supply of nitrogen to the crop". An analytical model of nitrogen supply to a crop would need to describe the decomposition of soil organic matter (an important supplier of nitrogen to plants). It would need to describe the atmospheric deposition of nitrogen (with 10 to 40 kg N/ha/year not to be ignored) and the binding of atmospheric nitrogen by symbiotic and autotrophic binders. It would have to account for nitrogen applied with manure and commercial fertilizers. It would need to describe nitrate losses by leaching and losses of ammoniacal nitrogen through volatilization. It would have to describe interactions among all these processes, *eg*, because it is likely that nitrogen losses increase with fertilizer application and that binders of atmospheric nitrogen decrease their activity after fertilizer use when metabolizable nitrogen is amply "available". And the model would have to quantify the recovery of "available" nitrogen by the root system as a function of a score of environmental variables. All this adds up to an elaborate model with massive data needs, which would probably generate results that were exceedingly expensive and not very accurate. And one might wonder whether there was a need for such models if one can remedy any problem of nitrogen deficiency by applying an adequate dose of manure or commercial fertilizer that is readily available and affordable. Similar considerations apply to the modelling of (the consequences of) weeding, or the lack thereof; or of plant protection (largely conditioned by the population dynamics of individual pests, which are in turn influenced by, inter alia, the weather that is "expected"). One can of herbicide or pesticide might eliminate the problem altogether! If you want it straight: "It is impossible to describe low-input farming accurately with analytical models. We can handle neither the complexity nor the data needs."

The situation is less complicated if one considers high-input farming, and quite comfortable if one is dealing with the limited complexity of strongly simplified "production situations", *ie*, of hypothetic land use systems in which limiting (land unit) attributes are supposedly "corrected" through plant protection measures, fertilizer use, irrigation or drainage. If all correctable limitations are indeed eliminated, a system's biophysical performance would only be limited by the amount of incoming solar energy (radiation), the temperature, and the crop's photosynthetic properties. In glasshouses, even light and temperature can be optimized, and production is limited only by the properties of the crop. This explains why in Dutch glasshouses tomato production reaches an incredible 50 kg/m/year or 500 tons/ha/year.

The production calculated for a fully optimized production situation is normally greater than the production realized in commercial farming, and much greater than the output of subsistence farming; it is not the actual production but the biophysical production potential. The "yield gap" between calculated production potential and observed actual production results from the compounded effects of all limitations that confront a real-world farmer but that were supposed "corrected" in the optimized/simplified system. ("Production gap" would be a better term in this context: "production" refers to the total production of dry plant matter; "yield" denotes only the harvested produce and is normally a fraction of production.) If considered in relation to the biophysical potential, the yield gap reflects the seriousness of all limitations in a land use system. It is thus a "land quality indicator".

The biophysical crop production potential differs between years, in response to differences in available solar radiation and temperature. The same variations in sunshine and temperature conditions also affect the actual (farmer's) production but a positive correlation between calculated reference production and observed actual production cannot always be expected. On the contrary, in a situation with much sunshine and little rainfall, the calculated production potential would be high (high rate of assimilation under surmised optimum water availability), whereas actual production might be sharply depressed by severe drought. For this and other reasons, the (reference) biophysical production potential is frequently replaced by the "water-limited production potential", *ie*, the production potential of a system in which nutrient supply, plant protection and harvesting methods are optimized, and production and yield are entirely conditioned by the sunshine, temperature and actual water conditions over the growing period.

Note that the water-limited production potential is less than the biophysical production potential in systems with less than optimum availability of water. Under such conditions, a smaller gap exists between the water-limited production potential and actual production than between the biophysical potential and actual production. The difference between the two gaps represents the part of the yield gap that was caused by sub-optimal availability of water.

Calculations of the water-limited production potential must keep track of the actual quantity of soil moisture stored in the rooted surface soil at any moment in the crop cycle, and match "water availability" with "demand for water by the crop". That is an added complication; the simpler model of the biophysical crop production potential assumed the land quality "water availability to the crop" to be non-constraining. The greater data needs and the more elaborate algorithm needed to calculate the water-limited production potential are associated with greater cost and greater errors. Sad but still acceptable: the water-limited production potential is (normally) a realistic indicator of the biophysical possibilities of advanced farmers who can afford to correct "low-cost" limitations with herbicides, pesticides and commercial fertilizers. The water-limited production potential tends to fluctuate strongly between years (often more strongly than the biophysical potential) and correlates better with actual production than the biophysical potential does. As a reference value, "water-limited production potential" is generally preferred to biophysical production potential despite the greater data needs and error margin.

Monitoring the total above-ground dry plant mass (*eg*, through remote sensing) and comparing it with the (reference above-ground) production potential calculated for a corresponding production situation would produce a time- and site-specific land quality indicator with direct relevance for early warning studies. It is even conceivable that reference production potentials could be estimated some time before the end of the crop cycle by substituting long-term average weather data for as yet unknown real data. Combining land quality indicators and estimated reference production might produce a workable crop yield forecasting procedure. The practical implementation of this hypothesis is now being studied in SAIL projects in Zimbabwe and China.

WHY DON'T YOU TRY THIS OUT?

Publishing conference proceedings on CD-ROM has the advantage that models can be added to a hypothesizing paper like the one presented here. The crop production model and the (sample) data files prepared for this purpose are "packed" in file PS123.ZIP on the CD-ROM. Activating hyperlink "Install PS123" under the yellow button "Related Papers" on the CD-ROM will unpack all files and install them in two new directories: C:\PS123 and C:\FAOCLIM. You need 2 Mb of free space on your hard disk to accommodate all files.

It is warmly recommended that you read file "demo.123" in directory C:\PS123. This (ASCII) file describes data file structures and model operation; it can be copied to your printer or viewed with any text editor. Detailed information on the structure of the model and on the functional relations used are given by Driessen and Konijn [1].

The sample data files provided are:

(1) generic soil data file "soil.dat"

(2) generic crop data file "crop.dat"

(3) 10 consecutive years (1981 to 1990) of daily weather data recorded at Quzhou weather station in the North China Plain. These files are called "Quzhou81.dat" through "Quzhou90.dat".

After invoking the program by activating directory C:\PS123 and typing PS123 <Enter>, you are guided through a series of questions on the screen. Read the disclaimer on the intro-screen and press any key.

The next screen asks questions about the site and year of weather data that will be used in the calculations (*eg*, Quzhou <Enter> and 83 <Enter> will make the program load weather data recorded at Quzhou in 1983).

The following screens invite you to specify the file that holds "your" crop data and to make a choice from the crops/varieties on file. For this demo version, you type "crop.dat" <Enter> and choose either (1) "generic maize" or (2) "generic winter wheat". (Winter wheat and maize are grown in rotation in the North China Plain.)

You will then be asked if you wish to calculate (1) the biophysical production potential, PS1, or (2) the water-limited production potential, PS2. Select option (1).

All biophysical data needed are now known to the program but some vital management information is still missing, *ie*, the day at which the seedlings emerge and the quantity of seed sown per ha. It is suggested that you do as the Chinese do: choose emergence of maize to take place around day 160 in the year (*ie*, sometime in June) and answer that 25 kg of maize seeds are applied per ha. If you choose to grow winter wheat, you set emergence at day 290 and apply 150 kg of wheat seeds per ha.

After all calculations have been done, a summary table (see Table 1) appears, which lists from left to right:

(1) DAY (*ie*, the day in the year, or in the next year if appropriate)

(2) LAI (leaf area index)

(3) ECe (the electric conductivity of a saturated soil extract; in dS/m)—only under PS2

(4) LIVSLEAF (living leaf mass; in kg/ha)

(5) SROOT (root mass; in kg/ha)

(6) SSTEM (stem mass; in kg/ha)

(7) SSO (storage organs, *ie*, ears for wheat or cobs for maize; in kg/ha)

(8) TDM (total dry plant mass; in kg/ha)

TABLE 1 Summary table of constraint-free maize grown at Quzhou 1983

Production situation 1: MAIZE (generic file) is grown at Quzhou83 from DAY 160 onwards

DAY	*LAI*	*Ece*	*LIVSLEAF*	*SROOT*	*SSTEM*	*SSO*	*TDM*	*CFWATER*
160	0.01	0.00	8	8	4	0	20	1.00
170	0.09	0.00	46	44	22	0	112	1.00
180	0.44	0.00	261	213	116	0	590	1.00
190	1.99	0.00	1094	776	479	0	2350	1.00
200	4.22	0.00	2350	1544	1691	0	5585	1.00
210	5.68	0.00	3180	1972	3872	73	9096	1.00
220	5.56	0.00	3181	2059	5732	1120	12102	1.00
230	4.50	0.00	2615	1951	6902	3704	15228	1.00
240	3.35	0.00	1973	1820	6245	7382	17636	1.00
250	1.75	0.00	927	1695	5634	9589	18772	1.00
261	0.02	0.00	0	1574	5067	10069	18454	1.00

(9) CFWATER (ratio of the actual and maximum transpiration rates). The value of CFWATER indicates the effect of drought stress on assimilation and is, by definition, always equal to 1.00 under PS1.

Table 1 summarizes the growth of a maize crop (as defined by “crop.dat”) that was sown around 1 June 1983; emergence was on day 160 (10 June). Note that the crop reached maturity on day 261 (and can be harvested some 10 days later after drying to a moisture content of 12 to 15 percent). Assuming that some 85 percent of SSO is grain and that the grain has 12 to 15 percent moisture at the time of harvest, the yield component would be around 10 tons/ha. The total production of dry plant matter amounts to 18.5 ton/ha, which accords with some 20 tons at 10 percent moisture.

Table 2 summarizes the performance of the same crop if grown under rain-fed conditions. Choose to examine another scenario (same site, same crop), select the option “water-limited production potential (PS2)” and answer the questions on soil information (file “soil.dat”; option 4: “Loams”) and on the initial electric conductivity (ECe; set at 4 dS/m which suggests a non-saline soil). Choose an initial soil moisture potential of 1000 hPa (or cm) and a surface storage capacity for water (ASSC) of 1 cm. There is no water on the land at the time of emergence (SSC = 0). The initial groundwater depth is 250 cm and the option “F” (= “fixed”) applies forced drainage that is installed in the area at a depth between 250 and 300 cm.

Note that development of the rain-fed crop is faster than under PS1 (maturity is reached on day 257 rather than 261 as shown in Table 1); the LAI values are less (less assimilating leaf mass) and the productions of “storage organ” (SSO) and “total dry mass” (TDM) are reduced to 3706 and 7363 kg/ha, respectively. The column CFWATER indicates that transpiration already lags sharply behind the theoretical maximum value only three to four weeks after emergence (CFWATER = 0.37 on the 30th day in the crop cycle).

The column ECe in Table 2 suggests that the electric conductivity (saturated soil extract!) of the rooted soil compartment increases from 4.00 dS/m at emergence to 4.22 dS/m on day 257 (*ie*, mid-September 1983). This increase might be undone by the next winter rains.

You might wish to run another scenario: answer the question “Is irrigation applied?” with “Y” and define an irrigation schedule. Be realistic: use between 3 and 8 cm of water per application and observe realistic irrigation intervals (basin or furrow irrigation is applied in the area and sprinkler or drip irrigation is not an option). Remember that Table 2 suggests that the first application of irrigation water would be needed around the 25th day in the crop cycle.

If you have chosen to examine a winter wheat crop, you will be surprised with a summary table that presents the most important system specifications with 30-day intervals, rather than 10-day intervals as in the case of summer maize. The program tries to accommodate the summary table on one screen. You’ll notice that the crop reaches maturity on day 158 in the next year (1984). Note the state of dormancy during the cold winter and the resumption of growth in the spring of 1984. The calculated biophysical yield potential amounts to some 7.2 tons per ha; the total dry mass is 13 tons per ha, equivalent to some 13 to 14 tons of “above-ground plant matter” at “harvest moisture content”.

The model suggests that growing this wheat crop rainfed might not be a good idea. If the initial soil moisture potential, surface storage characteristics, water table depth and salinity values are chosen as in the above scenario for maize, the crop fails (a “false start”). Starting 10 days later results in a calculated rain-fed yield potential of a mere 300 kg per ha. You could remedy the situation by irrigating the crop: a sample run with eight applications of irrigation water (3 cm water of 1 dS/m on days 75 and 100, 4 cm on days 120 and 140, 5 cm on day 160, 7 cm on days 180 and 200, and finally 5 cm on day 215 in the crop cycle) resulted in an expected water-limited yield potential of 6.9 tons per ha. Note that this irrigation input of (a total of) 38 cm of water was insufficient to lower the salt content of the rooted soil compartment. One might try other scenarios, *eg*, with better quality irrigation water, or with smaller but more frequent irrigation applications.

Examining alternative irrigation schedules is just one application of quantified production situation analysis. You can change the weather specifications, soil specifications, crop specifications and any or all of the management attributes. You can also substitute long-term averaged weather data for as yet unavailable measured data, and calculate “expected” yield potentials. The utilities

TABLE 2 Summary table of rain-fed maize grown at Quzhou 1983

Production situation 2: MAIZE (generic file) is grown at Quzhou83 from DAY 160 onwards; the plot is on Loams (PSlinit = 1000 hPa) and is 0 times irrigated; initial Ece is 4 ms/cm

DAY	*LAI*	*Ece*	*LIVSLEAF*	*SROOT*	*SSTEM*	*SSO*	*TDM*	*CFWATER*
160	0.01	4.00	8	8	4	0	20	1.00
170	0.09	3.97	46	44	22	0	112	1.00
180	0.44	4.07	261	213	116	0	590	1.00
190	1.99	4.05	1094	776	479	0	2350	0.37
200	2.31	4.08	1242	947	698	0	2887	0.12
210	1.93	4.12	1088	916	842	26	2871	0.95
220	2.05	4.20	1179	966	2212	909	5282	1.00
230	1.56	4.21	893	906	2743	2948	7585	0.55
240	0.89	4.21	497	845	2480	3859	8020	0.53
250	0.00	4.22	0	787	2239	3871	7695	0.00
257	0.00	4.22	0	754	2105	3706	7363	0.00

"selexion.exe" and "amdascon.exe" in the directory C:\FAOCLIM can help here. Read "demo.123" in directory C:\PS123 for instructions and a word of caution. Do keep in mind that the soil and crop data provided are default values. They can never replace calibrated/verified values and are supplied only to illustrate the procedure.

AN ADDED CONSIDERATION ...

The earlier observation that "achieving sustainability is an equilibrium problem" is of general validity: the precondition of "equilibrium" applies at all scales and to all aspects of land use. If sustainable land use is to be achieved in practice, we cannot limit our attention to biophysical supply and demand. We cannot ignore, inter alia, the socio-economic context.

We who study land use and land suitability for crop production focus our attention on the supply side. At the macro scale, prospects for supplying more food using less destructive methods are bleak. Unused land areas tend to have a marginal suitability for arable cropping (at best!), and increasing yields on existing farm land requires resources that are not normally available and knowledge that must be acquired in a process of learning and experimentation. In the meantime demand is growing at an alarming pace!

It is the author's considered opinion that sustainability cannot be hoped for if population growth is not brought under control. Our present efforts in this direction seem to be sadly inadequate. We are moving ever farther away from equilibrium.

REFERENCES

1 Driessen, P M and N T Konijn. 1992. Land-Use Systems Analysis. Dept of Soil Science and Geology, Wageningen Agric Univ, 216 pp.

2 Pieri, C, J Dumanski, A Hamblin and A Young. 1995. Land Quality Indicators. World Bank Discussion Papers No 315, Washington DC, 51 pp.

RESUME

La "suffisance" de propriétés d'unité des terres peut être mesurée en contrôlant des paramètres sélectionnés de systèmes et en comparant ceux-ci avec des valeurs calculées par une "situation de production" définie de façon rigoureuse. Une analyse de système d'utilisation des terres doit prendre en compte la dynamique du système. La complexité des systèmes actuels d'utilisation de terres défie l'analyse dynamique. Des systèmes "simplifiés", dans lesquels des limitations telles que des déficiences nutritionnelles, l'envahissement des mauvaises herbes, pestes/maladies, pertes de récoltes et "volontés de Dieu" sont assumés, remédiés au travers d'activités de gestion appropriée, peuvent être pris en main, mais les masses de plant calculé (organe) reflètent la performance potentielle plutôt que celle du système actuel. Ils peuvent néanmoins être valables: la définition d'unités de terres en termes de leurs plus "pertinentes" qualités assure que beaucoup de variations dans la performance des systèmes actuels d'utilisation des terres se retrouve dans les analyses de systèmes simplifiés qui ont une fonction de référence. L'analyse du "déficit des récoltes" entre la référence calculée et la performance observée des systèmes actuels, en utilisant au maximum l'information géographique pour faciliter la régionalisation à partir d'analyse par points jusqu'à une analyse des terres, est une façon d'examiner la durabilité des systèmes actuels d'utilisation des terres. Cette approche est actuellement examinée dans des projets de recherche en coopération en Chine et au Zimbabwé.

RESUMEN

La "suficiencia" de las propiedades de unidades de tierras se puede calibrar mediante el monitoreo de una selección de parámetros de sistema y la comparación de estos con los valores calculados a partir de una "situación de producción" rígidamente definida. El análisis de los sistemas de uso de las tierras debe tomar en cuenta la dinámica de los sistemas. La complejidad de los sistemas actuales de uso de las tierras desafía el análisis dinámico. Sistemas "simplificados", en los cuales limitaciones tales como deficiencia de nutrientes, infestación por malezas, pestes y enfermedades, pérdidas de cosechas y "Actos de Dios" se asumen remediados mediante actividades apropiadas de manejo, pueden ser examinados, pero las masas de planta (órgano) calculadas reflejan el funcionamiento potencial del sistema más bien que el actual. Sin embargo, estos sistemas simplificados pueden ser valiosos: la definición de las unidades de tierras en términos de sus calidades más "relevantes" asegura que una gran parte de la variación en el funcionamiento de los sistemas actuales de uso de las tierras se encuentra en el análisis de sistemas simplificados que tienen una función de referencia. Una manera de examinar la sostenibilidad de sistemas actuales de uso de las tierras es mediante el análisis de la "brecha de rendimiento" entre la referencia calculada y el funcionamiento actual observado de los sistemas, con un uso máximo de información geográfica para facilitar la regionalización desde el análisis de puntos hasta el análisis de tierras. Este enfoque está siendo ensayado en proyectos cooperativos de investigación en China y Zimbabwe.