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Contents

RESEARCH ARTICLE

1 Interdisciplinarity and Responsibility for Land Use, GIS and Eco-systems: Some problems of social traps

Hans Lenk

PERSPECTIVE

7 Responsibility for Eco-systems and problems of social traps and dilemmas

Hans Lenk

RESEARCH ARTICLE

16 Decoupling of greenhouse gas emissions from economic growth in Cameroon

Jean Engo

29 Barriers related to the deployment of renewable energies in Cameroon and ways to strengthen policies

Jean Engo

39 Ecologic and economic estimation of land productivity spatial heterogeneity in forest-steppe zone

V.M. Starodubtsev and R.M. Basarab

RESEARCH ARTICLE

Interdisciplinarity and Responsibility for Land Use, GIS and Eco-systems: *Some problems of social traps*

Hans Lenk

Abstract: Interdisciplinary studies and cooperations are necessary for practical work as well as studies in geodesy. Responsibility is a function of power, impact and knowledge. The more strategically central one's position is in terms of power, influence and knowledge, the higher one's responsibility is. This is an idea which can be worked out in more detail by using interdisciplinary approaches and distributive models on different levels. Social traps, Prisoners' Dilemma situations, *etc*, as pertaining to land, soil, and environment as well as some examples from geodesics and the study of the usage of nature systems like lakes and flood plain areas are discussed regarding responsibility and distribution problems. "Naturalists' Dilemmas" (or "Enjoyers' Dilemmas") are sketched and potentially solved by proposing a viable distribution strategy.

Keywords: land use, GIS, Eco-systems, social traps, geodesy, interdisciplinary studies

1 Interdisciplinary studies are necessary also for geodesy, GISs, *etc*.

Methodologically speaking and also in engineering and planning practice different sorts of interdisciplinary cooperations seem to be conducive and even necessary in geodesics as an earlier study[?] hypothesized and partially substantiated. In this preliminary article different kinds of interdisciplinary cooperation were mentioned as being useful in geodesy, notably for applying GIS models. We sketched the application of some such cooperation forms for examples of flood plain area management problems in England. Here is a short introductory outline of the paper:

A specific example project of an interdisciplinary integrated floodplain area development based on GIS methods was used to highlight some of the modeling, data acquisition and data integration problems as well as the interdisciplinary function of GISs in this realm of research and planning (theory).

There is a rather encompassing trend towards crossdisciplinary systems in an ever more interlaced world which is to a considerable part encroached on by man. This development comprises complex systemic trends getting ever more comprehensive impact to manipulate and reshape if not revolutionize our environment and the social world. We seem to live in a rather "socio-technological", largely manmade systems-technological and thus in a sense "artificial(ized)" world.

Systems methods and methodologies prevail. This trend is to be found in all science-induced technological developments as well as in administrations. Besides systems theory in the narrow sense the mentioned methods are characterized by operations technologies led by (methodical or even methodological) process controlling and systems engineering, by operations research, *etc*. Moreover, methodological assessment as articulated in philosophy of science is necessary.

In general, digitalization, abstraction, formalization and concentration on the operational procedures as articulated is essential. It is by the way of computerization and informatization as well as by using of for-mal and functional operations technologies (*e.g.* flow charts, network approaches, *etc*.) that the formal essentials of increasingly comprehensive processes, organizations as well as the interrelations of different fields and subfields are integrated. Information technologies lead the way.

For comprehensive systems engineering or system technology, it is indeed characteristic that the different technological developments including economic and industrial changes lead to system(at)ic interaction and generally to a kind of systems acceleration across different fields. (This is a trend which had been predicted by Gottl-Ottlililienfeld (1923) in 1913.[?] He had already described mutually interactive spill-over effects, ramifi-

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* **Correspondence to**: Hans Lenk, Institut fr Philosophie, Karlsruhe Institute of Technology, Karlsruhe, Germany; Email: hans.lenk@kit.edu

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cations across traditional realms and a sort of what we nowadays would call positive feed-back processes.) All these ongoing processes necessarily require a farreaching, if not encompassing interdisciplinary interaction and stimulation (*inter-stimulation*). Indeed, interdisciplinarity led by spillovers from science to science and from there to technological development and innovation plus implementation as well as to society at large is prominent nowadays. Systems analyses and systems technologies require interdisciplinary approaches in practice. The pertinent challenges within this *world of systems* including techno-systems (in fact socio-technical systems combined with social and ecosystems) requires a thorough methodological study for the types of interdisciplinarity in research and development and practise.

Short of providing such a methodological analysis here, it may suffice just to mention that one has to elaborate criteria for the methodological distinction of disciplines according to the objects and areas as well as scopes of the research, development and prospective implementation. Relevant (arsenals of) methods and knowledge interests (Habermas) have to be articulated and the relationship between theory and practice should be studied. Methodologically important is the difference between theories and their systematic and historical connections and contexts, substantivity vs. operationality of theories (substantive vs. operative or procedural theories).[?] One has to specify from a philosophy of science perspective the extant patterns of explanation and systematization (descriptive versus explanatory, historical versus systematical) and questions of cognitivity and normativity (descriptive versus normative approaches and practical combinations).

These perspectives lead to different types of bi- and multilateral interdisciplinary relationships between the respective disciplines of these as, *e.g.*, in GIS engineering. Stages of the more or less strong, formal and law-based interpenetration or merely aggregative coordination are reflected in the following

Types of Interdisciplinarity:

1. Interdisciplinary co-operation in more or less well-defined projects (*e.g.* GIS in geology)

2. Bidisciplinary or interdisciplinary research area (like satellite geodesy)

3. Multidisciplinary aggregate field of research (*e.g.* environmental research)

4. Genuive interdiscipline (like physical chemistry or biochemistry)

5. Multidiscipline resulting from/relying on multidisciplinary theoretical integration

6. Abstract generalized interdisciplinary systems theories (*e.g.* general systems theory)

7. Mathematical theories of abstract and complex dynamical systems (*e.g.* deterministic or an as yet less developed probabilistic chaos theory)

8. Supra-disciplinary abstract structure-analytic and operational disciplines (*e.g.* operations research)

9. Methodological supra-discipline as *e.g.* philosophy of science and science of science

10. Philosophical and methodological epistemology as a meta-disciplinary approach (*e.g.*, methodological schema interpretationism, cf. Lenk (1993)).[?]

At first, we have the co-operation of different experts for or within a developmental programme, as *e.g.* in a coastal zone management (CZM) planning where experts from different fields like geography, cartography, hydrography, geodesy, biology and ecology, limnology or oceanography as well as engineering in dike-building and landscape planning have cooperated.[?] Secondly, an interdisciplinary or bidisciplinary realm of research like satellite geodesy might evolve or, thirdly, even a multidisciplinary aggregative research area as, *e.g.*, environmental research (systematic ecology). The fourth level or step of co-operative integration would amount to a real interdiscipline (like molecular biology or population genetics) or, fifthly, a multidiscipline in the more specific sense (multidisciplinary theoretical integration) (for instance the integration of natural and social science approaches in systems engineering of ecotechno- sociosystems, *e.g.* diked areas and CZM. The sixth through eighth levels are formal theories of an abstract mathematical brand being used as instrumental vehicles of modeling real or constructed systems - including approaches in Social Impact Analyses of geosystems engineering. Furthermore, the metatheoretical levels 9 and 10 are addressed on a higher stage of methodological or epistemological (meta-)analyses (*e.g.* philosophical, social and methodological assessments).

Interesting questions regarding GISs and their application to CZM are:

a) On what level are actual and potential interdisciplinary co-operations in both of these fields to be located?

b) How can possibly and already do levels and types of interdisciplinary interact with one another?

c) Is it possible to distinguish and effectively separate descriptive and normative, *i.e.* prescriptive or (e)valuative, utilization of interdisciplinary modeling, *e.g.* with regard to factual ("cognitive") and interest or value conflicts, respectively?

d) Can we neatly distinguish between scientific and purely descriptive analyses and evaluative approaches in the practice of systems planning, to wit, *e.g.*, coastal or shore zone management?

e) To what extent are values, goals and interests ("humanware" so to say) indispensable moderating variables for any application of GISs and planning procedures, *e.g.* coastal management acts and plans?

With respect to the evolved types or stages of interdisciplinarity, we would hypothesize and argue that the practical elaboration of GISs and the interdisciplinary collaboration in landscape, land-use and coastal as well as lake and river shore management have thus far not progressed beyond step 3 as in the list of types of interdisciplinarity above (if not only step 2) and will in the foreseeable future hardly reach level 5 of a really theoretical multidisciplinary integration. (This judgement is based on the rather as yet underdeveloped stage of the theoretical integration of natural and social science approaches in general and notably with respect to sociotechnological applications.) Yet, advancing interdisciplinary approaches in all of these mentioned fields will turn out to be necessary for and conducive to practical applications in the near future.[?]

2 Social traps, Prisoners' Dilemma situations, *etc*. as pertaining to land, soil, and environment

In economics and social science scholars speak of social traps, the externalities problem, side-effects, social costs, the Prisoners' Dilemma, and the public goods problem. I would like to illustrate the problem first by using the problem structure of the so-called "*Tragedy of the Commons*".[?] This constellation can be understood as a prototype of a social trap. The central question will turn out to be: Who would bear the responsibility for an action result and for the respective consequences which nobody had wanted or intended beforehand?

According to Hardin every owner of stock in the Sahel zone has an individual and perfectly legitimate interest in utilizing and exploiting the common grassland, the so-called "common", which is indeed a collective good. This individual interest is characterized by striving to have as much stock as possible, because the greater one's own stock, the higher is one's social status. All the owners and society in general, however, have a common interest, a real commonality, namely to avoid overgrazing of the commons. This constellation of individual and common interests would lead to the following dilemma: Because hardly anybody has sufficient individual interest to avoid extensive exploitation of the commons for one's own good, everybody will utilize it as extensively as possible. Therefore, overgrazing of the commons would be the necessary result. Consequently, in the last analysis the very satisfaction of the individual interest would be barred or ruined, respectively. Hardin thinks it necessary to have social,*i.e.* not merely individual, mechanisms of control, in order really to avoid such a dilemma. Socially enforced cooperation, *e.g.*, would be such a controlling mechanism. He emphasized that such "tragedies of the commons" would undermine or at least relativize the well-known traditional theorem of "the invisible hand" after Adam Smith. (The so-called "invisible hand" in terms of the market mechanism would according to the opinion of classical and neoclassical economists result in such a constellation that the consequences (profit or loss, respectively) would be attributed to the responsible agent and that an optimum overall result in terms of an optimal equilibrium and general wealth,*i.e.*, a Pareto optimum would ensue.) According to Hardin the rational maximizing of each individual interest need not, via dynamic market processes, lead to an optimum result and wealth for all. On the contrary, it may lead to depletion, erosion and pollution, *etc*., of the common land. A similar problem with respect to arable land use also leads to depletion, erosion, even devastation of arable land in large parts of Africa: the few remaining trees and shrubs are necessarily used up and/or consumed to satisfy pressing survival interests of individual families. This consumption leads to further expansion of the desert and to an additional deterioration of sustenance and survival conditions of the whole population, *etc*. (With respect to stock and the above mentioned traditional conflict between the individual owners' interests and social needs even the boring of additional wells might indeed aggravate or escalate the conflict constellation and accelerate the ecological problems. This might be a well-known unintended side-effect of political and economic development programs.

A similar effect is the clearing and making arable of tropical rain forests on basically poor soil which might lead to local and regional erosion and depletion of the ecosystem and to a continental or even global change of the climate (cf. the global carbon dioxide plus methane problem and the impending glass house effect of "overheating" the atmosphere as well as the socalled climate crisis). Again, also the problem of environmental pollution turns out to be of analogical or equivalent structure. The absence of pollution, a public good indeed, is not diminishing or decreasing in size, but instead a *negative quality* is added, namely through the depositing of refuse of many kinds. Again, it seems more profitable, *i.e.* cheaper, for the agent to do away with garbage on public soil, *e.g.*, to deposit chemical refuse in the Rhine. As a consequence of these public measures external social costs would result. Negative external effects which would amount to a burden for the general society; they can only be avoided or redirected if the taxpayer or everybody pays in money or is suffering in terms of health disadvantages, deterioration of quality of life or aesthetic values of ecosystems and the landscape. Externalities would result from the actions of producers and consumers whenever these agree on actions which would be disadvantageous for the environment (think of the example of the one-way bottles). Therefore, there is also a responsibility of consumers, co-responsibility with respect to the protection of the environment. On different levels of a scaling phenomenon all members of a society would bear a certain responsibility for an acceptable or good and healthy state of their respective society.[?] Generally speaking the same structure is to be found with many problems of social constellations that may be dubbed as *social trap constellations*. It would be "profitable" for individuals to infringe social rules and norms as long as (almost) all other members are abiding by them.

A similar structure is to be found in the so-called *Free-Rider Problem* and *the assurance problem* with respect to providing and maintaining collective and public goods. Both cases lead to social traps. The dilemma of environmental protection on a voluntary basis is an intriguing example of this constellation. The free-rider problem is "A barrier to successful collective action or to the production of a public good that arises because all or some individuals attempt to take a free ride on the contribution of others. Non-contributors (would) reason as follows: Either enough others will contribute to achieve the good or they will not, regardless of whether I contribute or not; but if the good is achieved, I will benefit from it even if I don't contribute. Consequently, since contributing is a cost, I should not contribute".[?] Likewise, "*the assurance problem*" is "a barrier to successful collective action or to the production of a public good that arises when all or some individuals decide not to contribute to the good in question because they lack adequate assurance that enough others will contribute".[?] The provision and maintenance of a collective good is according to Olson (1968) primarily dependent on the magnitude of group membership: The greater a group of participating individuals, the less the chance and opportunity turn out to be for providing and maintaining such a good and the greater is the necessity of compulsion, sanctions, *etc*.[?] with respect to usage and distribution of collective goods. Whereas community norms or mores would still seem satisfactory for reaching a common goal in small groups, this does not apply to large groups. Buchanan called this phenomenon "the large number dilemma".[?]

The structural problems of social and individual actions, of public goods, and of the commons and social order can easily be illustrated by using the well-known game theoretical model of the so-called *Prisoners' Dilemma (PD)*. A detailed analysis of the PD structure shows that strategic actions of competing selfinterested rational agents lead to a result which turns out to be an unintended social consequence putting all participants on a worse level than a cooperative strategy of abiding by social rules would have obtained. PD-constellations cannot be solved on a pure individualistic level.

The above-mentioned dilemmas are at the same time examples of *rationality traps*: the individually rational action strategy leads to collective social irrationality undermining the first one. Under certain conditions, individual rationality can be self-destructive.

A second problem of *distributing responsibility* does not result just from collective corporate action by itself, but only if many people act *under strategic (competitive) conditions*, if negative external, synergistic and/or cumulative effects occur. Indeed,"strategic condition" means that the final result is dependent on the (relatively independent) acting of many individual agents. Synergistic and cumulative effects would only result, if different components have a joint and mutually escalating impact. The individual components might by themselves be (relatively) harmless, but eventually they would result in the deterioration, depletion or even loss of a highly valued common good (think of the example of the continental European forest "dying" from pollution by acid rain and erosion or, recently, microor fine dust by urban car traffic, *etc*.).

3 Extended responsibility and eco-liability

The distribution problem of responsibility, *e.g.*, consists in the fact that frequently side-effects cannot be attributed to a single originator and that they usually were/are or even could not be foreseen or predicted. We have two partial problems here: First the question of participatory responsibility with respect to cumulative and synergistic harmful effects and second the question how to responsibly deal with unforeseen or even unpredictable facts or side-effects. The first problem can be called the problem of distributing responsibility under strategic conditions. For instance, is the legal principle of attributing "causality" and responsibility valid in Japan since the case of the Minamata disease according to which the statistically assessed contribution to the common harm by relevant polluters in the vicinity is ascertained, by law, as the pertaining causality indeed satisfactory? The burden of proof here lies so to speak on the side of the potential originator, the polluter, who has to prove the harmlessness of his emissions. This reversal of the burden of proof seems to be at least a controllable and operational measure to allow for attribution wherever environmental damages are in question. In these detriments usually land, water and air use or misuse are combined. They can at least be as a rule forestalled or diminished in a controllable way by assigning sanctions. In that respect the Japanese legal principle of attributing causality might foster environmental protection. But there are methodological and legal as well as moral problems connected with such a regulation. First of all, adjacency and the guessing of causality can never be a proof of a causal origin. In addition, the problem is how to distribute or attribute the responsibility in the cases of synergistic and cumulative damages, particularly those with below-threshold-contributions of individual agents. Another problem is how to distinguish between a descriptive assessment of causal origination and the normative attribution of responsibility, between causal responsibility and liability after Hart (1968).[?] How could one possibly distinguish between the causal impact, the descriptive responsibility,*i.e.* the descriptive attribution of responsibility, and the respective normative attribution of responsibility for contributions the amount of which is individually ineffective, below the threshold of harmfulness? And how is one to distribute this kind of responsibility in general? Would it not be meaningful to postulate a normative collective responsibility of all pertinent corporations within the respective region in the sense of a joint liability? This would, however, mean a liability of all relevant corporations for the total damages. The impaired parties could sue for damages, claim in court for compensation and/or indemnification from any presumably participating corporation. Does this make sense, if connected with an overall generalization? This regulation, however, would have the advantage of dispensing with the proof of damage in respect of each singular damaging or aggrieving party as *e.g.* a respective norm in German Civil law would prescribe. This kind of regulation would, in some way independent of individual case argumentation, interpret all non-collective agents as quasi one corporative agent being liable in total. The internal distribution and compensation within this quasi-group of corporate agents would then be a problem of mutual bargaining of all aggrieving parties.

Not with standing these arguments another kind of total liability with respect to product safety and hazards in terms of environmental damages of public goods should be established. It should be noted that there is a European Community agreement as of 1985 with regard to product liability laws. Causal originators of damages would then/now be liable in the sense of a strict liability in tort, whether or not they are really guilty in terms of intent or only negligent. Causal origination would already ascertain descriptive causal action responsibility and with respect to the damage of a good to be protected also normative responsibility for the respective action and its consequences. This form of liability would hopefully be deterrent enough to prevent infringements. If, however, damages would nevertheless occur it would at least not be necessary to prove fault or guiltiness as a presupposition of any claim for compensation.

Is the human being because of the immense power of technical encroachment and feasibility beyond any beforehand imagination and control responsible for much more, so to speak, than (s)he could possibly foresee and literally (intentionally) be normatively responsible for? Should (s)he not take over responsibility for unforeseen or even unforeseeable side-effects of her or his actions with respect to technological and scientific big science projects? But how could one possibly do that? There is no way of really morally being held responsible for something one does not know or could not know. In the sense of causal responsibility (taken descriptively) one can be held responsible in some sense, even if an unintended damage occurs. The question however is, whether one could be held responsible in a normative-moral sense too. The so-called principle of causation if interpreted in a moral and legal sense, would - at least in tendency - adequately design normative responsibility also. One would have to answer for, to make good and to be liable for consequences in the sense of being liable to pay compensation, *etc*. The range and power of action seems to have multiplied to such a degree that anticipation cannot follow quickly enough or pursue all the complex ramifications of impacts, consequences and side-effects in complex interlaced systems. That seems to be an intriguing dilemma of responsibility in our systems technological age impregnated by complex systems interactions and dynamic changes easily transgressing linear thinking and traditional causal disciplinary knowledge. In principle this also pertains to eco-systems and their respective land bases.

Earlier, I dubbed the distribution dilemma regarding the using or enjoying a nature resource or eco-system by different users (*e.g.* fishermen and anglers, hobby sailors, rowers, swimmers, naturalists, *etc*. taking advantage of a lake) “the Naturalists’ Dilemma” or “Enjoyers’ Dilemma”. By contradistinction to the PD, this situation can be pragmatically tackled and the problems solved by delimitating, dividing and distributing spaces and/or times, certainly, *e.g.*, by mutual agreement.[?]

Technology, technological progress and economicindustrial development in combination with the respective damages for land, clean air and water turn out to be multi-dimensional phenomena asking for interdisciplinary and complex approaches. Multi-perspectivity is the result of an ongoing mutual interaction between diverse realms and actions of many corporate and individual agents. This is leading to a rather great complexity of individual, collective and corporate contributions, different areas and social background factors. The exponential structure of technological development in terms of range, energy, acceleration, interaction feedback phenomena, *etc*. is a familiar insight of traditional sociology of science, technology and economic development. This insight is generally true for any multiramified and interlocked socio-technical or social phenomena of development.

With regard to responsibility in general, it is not only corporations and institutions in economics and industry which have to bear responsibility, but also the state and its representative decision makers. Corporate responsibility has to be connected with individual responsibilities of the respective representative decision makers. This is true also for big technology projects, particularly if they are run by the state itself. There should be not only a legal, but also a moral balance of powers in terms of checks and controls similar to the traditional distribution of legal powers between legislature, government and jurisdiction.

The upshot of this in terms of moral responsibility might be formulated like this: The extension of individualistic responsibility is to be combined with the development of a socially proportionate coresponsibility, and with the establishment and analytic as well as institutional elaboration of corporate responsibility and a new sensitivity of moral conscience. Types of responsibility have to be analyzed in a more differentiated way than hitherto.[?,?,?,?,?,?] Only in this way we may be able to cope with the most complex structures of causal networks and the far-ranging consequences of human actions and social impacts. Concepts for a more social orientation of responsibility and conscience should be given most attention. Ethics and moral philosophy have to take serious these new systemic challenges by technically multiplied possibilities and impacts of action and system networks. An applied ethics of not only collective, but also of strategic and network actions as well as their consequences would seem to be urgently needed indeed in applied sciences - even in geodesic projects.[?,?,?]

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PERSPECTIVE

Responsibility for Eco-systems and problems of social traps and dilemmas

Hans Lenk

Abstract: Responsibility is a function of power, impact and knowledge. The more strategically central one's position is in terms of power, influence and knowledge, the higher his or her responsibility would be. This is an idea which can be worked out in more detail by using distributive models of graph theory and pre-distribution assignments of rights and duties according to different levels.

Keywords: Eco-systems, social traps and dilemmas

1 Ecological sins economical and/or moral

Our natural environment with its resources of landscapes, forests *etc.*. is not only to be considered as an asset highly appreciated for aesthetic, healthy and touristic aims and offers therefore unreplaceable opportunities for personal and group or family pleasures and nature experiences or sporting work-outs. Yet, natural resources always were and still are and will remain a source of great economic value for profitable exploitation. Think of the lumber and timber tradition and business. Under different aspects, "nature" is a treasure to capitalize on. Only recently, economists started trying to evaluate, if not theoretically commercialize, "nature" as a "capital" under divers economical terms.[1] And as such it is vied for, exploited under the standards of competition and markets *etc.*. And "nature" is almost everywhere in danger by now. Erosion, pollution, and other forms of industrial damages and degeneration of nature really looms large - as everybody knows by now - and many already "suffer" from such ecological deteriorisation - even in so-called "natural paradise" regions.

Ecological damages in the industrialized nations - if they can be assessed in monetary value at all - amount(ed) to about 3-5% of the Gross National Product (GNP). Yet, these damages are thus far not comprised in the GNP. What are the compensatory or defensive expenditures (amounting to about 10 % of some countries' budgets), which are indeed an increasing factor for the GNP, although their sole function is damage compensation?

To begin with, ecological damages and, for that matter, irreversible ones, can usually not simply be attributed to a single (individual) producer or responsible person. For instance, already as early as 1989 the external costs of environmental damages only concerning the field of motor traffic were assessed by the director of the Federal Agency for Environmental Protection, Wicker, at the level of approximately 25 billion US $. (By the way, the total assessment of man-made damages to the ecology for the very same relatively small country amounted to 103,5 billion German Marks.) But this also does not refer to individual damage attributions, with regard to somebody who is or many who are personally responsible although car traffic is usually mainly considered an individual affair in the first place.

There is no such thing as solely economical, technological action on a purely individual basis, each techno-economical action is embedded in - and therefore implies -social and socio-cultural contexts, is unavoidably a social action, and this applies to the same extent to the consequences of such actions. Usually every action has consequences for the environment, although not every consequence necessarily results from one single action itself.

The division of labor in corporations and large-scale projects on the one hand and the coordination of actions through markets on the other hand, but especially unwanted and yet unseen combinations of unfavourable factors, which are inclined to result in catastrophes, or even subliminal negligence or carelessness as with the so-called "normal catastrophes" analysed by Perrow will complicate the attribution of (unwanted) consequences

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* **Correspondence to**: Hans Lenk, Institut fr Philosophie, Karlsruhe Institute of Technology, Karlsruhe, Germany; Email: hans.lenk@kit.edu

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of actions, and the attribution of responsibility in all its kinds. The individualistic concepts of ethics and philosophy, technology and economy do not suffice to tackle these problems, they are obviously not adequate, since they usually focus almost exclusively on individual actions and not on interactive, collective and corporate forms of actions or structural and systematic contexts. Thus far ethical approaches have indeed been too much oriented toward individual persons, they have not paid enough attention to social aspect; the problems are not yet adequately adjusted to socio-ethics and social philosophy. This has been mentioned quite a while ago.[2]

It is true, so far the problems of complex constellations of causes and the problems of responsibility have been discussed only in a rather generalized way in philosophical literature, while jurisprudence is considering them in a much more detailed manner and has indeed come up with some very interesting approaches for solutions - which are of interest for philosophy as well.

In addition, generally speaking one should distinguish the external responsibility for the organization and corporate action from the internal problem of responsibility distribution. The same is true with respect to institutional moral versus personal moral responsibility, although certainly an indirect connection obtains to be traced and analysed case by case which however does not amount to a general definitional reduction of corporate responsibility to solely individualistic terms or factors.

Corporations can act intentionally and non-reducibly (in a "secondary" sense, on a higher supra-individualistic *i.e.* participatory, fictional, social level, which is symbolically and semantically structured and interpreted; their actions nevertheless are "real" in their effects, for example in their social effects). Such a corporate responsibility, which is not equivalent with the direct personal responsibility that only individuals have to bear, may apply not only to businesses but also to the state and corporations like associations of technicians and scientists or other professions. So far the traditional aprioristic linking of attributing moral responsibility to natural persons only with the concepts of responsibility defined but in individualistic terms seemed to set up insuperable barriers to the endeavour of attributing moral responsibility to corporations and institutions. Does this really and necessarily have to turn out like that? Have we failed in our efforts with respect to the development of exclusively individualistic models? Should we not rather develop a model with hierarchic levels that differentiates among the responsibilities on the various levels and takes them into account? This is a subject being under vital and differentiating discussion in the USA these days.

Rendering or making corporations responsible may represent a first step towards attributing responsibility for corporate actions; the problem of distributing responsibility (in corporations) has to be approached then in a further step. The latter has to be treated with a differentiation among the various types of responsibility as mentioned. However, division of labour will complicate the perception and acceptance of responsibility as well as the attribution of respective consequences of a technology to an individual's marginal part within the totality. Thus, the abilities to perceive and differentiate responsibilities need to be improved as well.

We must differentiate between the problem of co-responsibility, *i.e.* the distribution of responsibility to (contributing) individuals in corporate respectively non-corporate action, and the problem, whether or not corporations as such can be attributed a specific responsibility at all. The former topic consists of the question whether and how the various kinds of collective responsibility can be referred or reduced to individuals. (The moral responsibility of individuals should not - as we saw - be replaced or diluted by collective responsibility - individuals can be co-responsible.) This does not mean that collective responsibility is apt to be totally resolved or diluted into individual (moral) responsibilities in each case. Not every responsibility can be completely resolved into the respective individuals' singular responsibilities. Collective responsibilities may exist, that are not reducible to individual responsibilities "without remainder", although they are at least connected with individual responsibilities and should be of relevance for these. The analysis of the intriguing connections is an important task of further pragmatic moral philosophy which indeed presupposes the elaboration of rather differentiated concepts of types and levels without which the interconnections could not be traced, identified and analyzed.

In economics and social science scholars speak of the externalities problem, side-effects, social costs, social traps, the Prisoners' Dilemma, and the public goods problem. In the classical situation of the Prisoners' Dilemma two prisoners (A, B) are indicted for armed robbery. Both are offered to be chief witness and to come free without penalty. Both of them can only be convicted because of illegal possession of weapons. Therefore, if both remain silent, both have to expect only a rather minor punishment (of, say, one year in prison), but a much higher punishment (ten years), if one is convicted (punishment for the chief witness would be zero). Therefore, confessing seems to be preferable as the dominant strategy. If one of the two confesses, it is also profitable for the other one to confess, because then he would receive eight instead of ten years imprisonment. The amount of punishment is therefore not only dependent on one's own strategy, but also on that of the co-prisoner. Now the dilemma of the social trap consists in the fact that it turns out to be irrational for A as well as B in their own interest to confess (dominant strategy). But if both of them would act rationally, *i.e.* both would confess, they would incur a higher punishment (eight years each in prison) than if both would keep silent (only one year each), *i.e.* if they would act cooperatively. Individual rationality therefore leads to collective irrationality and self-damage.

We might easily conceive of a *positive* variant of the PD which we would like to call the Naturalists' Dilemma or, in more general terms, the Enjoyers' Dilemma or Environmentalist's (ED) with respect to scarce resources. Imagine the only lake in a nature-reserve (*e.g.* in a US National Forest) which is to be enjoyed and partially utilized by anglers and waterskiers at the same time. For the sake of argument the lake should not be that large that both could enjoy their sport at or on the lake without interfering with one another. If both the anglers and the waterskiers would use the lake unrestrictedly they would not to be able to enjoy their sport at or on the lake at all. The waterskier would mingle with the anglers' lines expelling and deterring the fish from the range of the anglers' reach. Thus, they apparently have to come to an agreement with one another in order to be able both to enjoy a nature reserve. They have to arrange for restrictions by, *e.g.* segmenting space or time. They might allot part of the lake to the waterskiers and the other to the anglers or they might for instance allow to waterski only every second day. Other possibilities of restrictions are conceivable. However, any restriction and segmentation whatsoever would decrease a full-scale enjoyment of both parties. Therefore, the dilemma which arises does not develop from the bargaining of negative sanctions as in the classical PD, but it is a dilemma of the full-scale enjoyment with respect to scarce nature reserve. In this variant, not sanctions of the object of the potential agreement, but the possibility and degree of positively enjoying the natural source or resource are at stake. It is largely the same idea as Hardin (1968) had in mind with the overgrazing of the Sahel zone. The most important difference from the PD is that in ED situations tiered possibilities or levels of opportunities of utilisation do occur (by contradistinction to the yes-or-no-strategies involved in the PD model) which admit of variations with regard to degrees or intensity of utilisation or even partially dispensing with them. Here, the pay-offs may - within limits - be at will determined or chosen by steps.

It might be as difficult to reach an agreement in this sort of Enjoyers' Dilemma as in the classical PD. However, it is not just a change in signs in the respective utility and evaluation functions, but different points of equilibria might occur.

Generally speaking, the positive variant of the Enjoyers' Dilemma seems to be of considerable interest besides the classical and static PD restricted to a bargaining of negative sanctions. The Enjoyers' or Naturalists' Dilemma seems not only to apply to the use of common land or nature reserves, but also to privately owned and exploited land if it is embedded in an endangered ecological environment, because the groundwater level as well as clean air or drought or polluted air, erosion and depletion would not stop at a conventional borderline, but affect the whole local, regional or even continental ecology. It certainly is a pressing problem, *e.g.* with regard to nature resources and recreation facilities in the vicinity of cities and larger metropolitan or 'metroplex' areas of dense population in particular.

The central point with respect to the problem of the distribution of responsibility is the question concerning the normative and descriptive "distributability" (susceptibility for distribution) in terms of the theory of action and the possibility of adequately reducing the collective responsibility to individual actors in relation to the form of collective actions and causations. Thus, the respective form of a collective action is of determining value and figures as a criterion for the distinction of various attributions of responsibility. Another important point is that the distribution of responsibility is dependent on the kind of responsibility: If one differentiates between a legal liability for compensation and moral responsibility, a distribution is (more) easily attainable with the first kind, while it might be not (so) easy with moral responsibility. In particular, the negative formulations of a responsibility for prevention of damages and the preservation of states of well-being *etc.*. are relevant for the distribution of responsibilities - as is the responsibility to prevent omissions, which is more easily accessible for a regulation of responsibility. One should also differentiate between the sufficient and the necessary conditions of a consequence or damage in relation to several involved persons' failures to act. So, the individual failure to act is causally sufficient for the occurrence of the consequence or damage, if non-omission of the act prevents this occurrence.

Thus, there exists an ethical obligation for humans to take care that especially humankind - as well as other natural kinds dependent on the human power for intervention - does not get extinguished. It is true that individual beings, which have not yet been conceived, have no individual moral or legal right to be born, and one cannot impose an individual obligation on particular human couples to procreate, but it seems to be a sensible extrapolation from the constitutional rights of humankind, which are else often only constructed as rights of repulse and protection, to develop a collective responsibility of today's living humans that they must not let their species be extinguished or destroyed. Humans have not only the - negative - responsibility to leave behind wholesome conditions of environment and life for future generations, which means they should not totally exploit non-regenerative raw-materials and should refrain from lethal poisoning, depletion and destruction of the environment. They collectively also have an obligation and responsibility to actively prevent this from happening and to work for a future existence of humankind in life conditions worthy of human beings. This is at least a moral demand which originates in the integrity and continued existence of humankind, which are considered the highest desirable values by various ethical systems. Even a version of Kant's (AA IV, 341) formal Categorical Imperative refers to the actual content of the "principle of humankind and of any reasoning nature" as things in themselves.

Judged morally, then, future generations' relative rights or quasi-rights to existence do exist, even though no singular existence of a non-conceived individual can be sued for on a moral or legal basis. Thus, certain general human and moral obligations transcend those which are individualistically and juristically concretized. Moral value commitments are more comprehensive and determining than moral or legal individual responsibilities. Morality is more than a singular individual responsibility or obligation.

2 Social traps, Prisoners' Dilemma situations *etc.* as pertaining to land, and environment

In economics and social science many scholars speak of social traps, the externalities problem, side-effects, social costs, the Prisoners' Dilemma, and the public goods problem. I would like to illustrate the problem first by using the problem structure of the so-called "*Tragedy of the Commons*".[2] This constellation can be understood as a prototype of a social trap. The central question here will turn out to be: Who would bear the responsibility for an action result and for the respective consequences which nobody had wanted or intended beforehand?

According to Hardin every owner of stock in the Sahel zone has an individual and perfectly legitimate interest in utilizing and exploiting the common grassland, the so-called "commons", which is indeed a *collective good*. This individual interest is characterized by striving to own as many animals as possible, because the greater one's own stock, the higher is one's social status. All the owners and society in general, however, have a common interest, a real *commonality*, namely to avoid overgrazing of the "commons". This constellation of individual and common interests would lead to the following dilemma: Because nobody has sufficient individual interest to avoid extensive exploitation of the "commons", but just strives for one's own good. Hence, everybody will utilize these "commons" as extensively as possible. Therefore overgrazing of the Sahel "commons" would be the necessary result and consequently in the last analysis the very satisfaction of the individual interests would be barred or ruined, respectively. Hardin thinks it necessary to have social, *i.e.* non-individual mechanisms of control, in order to avoid such a dilemma. A controlling mechanism would have to be socially enforced. Hardin emphasized that such "tragedies of the commons" would undermine or at least relativize the well-known traditional theorem of "the invisible hand" after Adam Smith.[3] According to Hardin the rational maximizing of each individual interest need not (and in the "tragic" dilemma situation *cannot*), via dynamic market processes lead to an optimum result and wealth for all. On the contrary, it must lead to depletion, erosion and pollution *etc.*., of the common land. A similar problem with respect to arable land use also leads to depletion, erosion, even devastation of arable land in large parts of Africa: the only few remaining trees and shrubs are necessarily used and/or consumed to satisfy pressing survival interests of individual families. This consumption leads to further expansion[2] of the desert and to an additional deterioration of sustenance and survival conditions of the whole population *etc.*. (With respect to stock and the above-mentioned traditional conflict between the individual owners' interests and social needs even the boring of additional wells might even aggravate or escalate the conflict constellation and accelerate the ecological problems. This might be a well-known unintended side-effect of political and economic development programs.)

A similar effect is the clearing and making arable of tropical rain forests on basically poor soil which might lead to local and regional erosion and depletion of the ecosystem and to a continental or even global change of the climate (cf. the global carbon dioxide and methane problem and the impending glass-house effect of overheating the atmosphere and the whole climate).

According to Hardin the problem of environmental pollution turns out to be of analogical or equivalent structure. The commons, a public good in this case, however, is not diminishing or decreasing in size, but instead a negative quality is added, namely through the *deposit-*

ing of refuse of many kinds. Again, it is profitable, *i.e.* cheaper, for the individual agent to do away with garbage on public soil, *e.g.*, to deposit chemical refuse in the Rhine as was traditional before 1900. (A clearance commission was installed only in 1908. As a consequence of these public measures external social costs would result.)

Negative external effects which would amount to a burden for the general societies. They can only be avoided, mitigated or re-directed if the taxpayer or everybody pays in money or is suffering in terms of health disadvantages, deterioration of quality of life or of aesthetic values of ecosystems and the landscape. So-called "externalities" (impacts from outside of the traditional economic model) would result from the actions of producers and consumers whenever these agree on actions which would be disadvantageous for the environment (think of the example of the one-way bottles). Therefore, there is also a responsibility of consumers, *e.g.*, co-responsibility with respect to the protection of the environment. On different levels of a scaling phenomenon all members of a society would bear a certain responsibility for an acceptable or good and healthy state of their respective society.[4]

Generally speaking the same structure is to be found with many problems of social constellations which can be dubbed *social trap* constellations. It would be profitable for individuals to infringe social rules and norms as long as (almost) all other members are abiding by them. A similar structure is to be found in the so-called *Free-Rider Problem* and the "assurance problem"[5] with respect to providing and maintaining collective and public goods. Both cases lead to so-called "*social traps*". The dilemma of environmental protection on a voluntary basis is an intriguing example of this constellation. The free-rider problem is "A barrier to successful collective action or to the production of a public good that arises because all or some individuals attempt to take a free ride on the contribution of others. Non-contributors (would) reason as follows: Either enough others will contribute to achieve the good or they will not, regardless of whether I contribute or not; but if the good is achieved, I will benefit from it even if I don't contribute. Consequently, since contributing is a cost, I should not contribute".[5]

The provision and maintenance of a collective good is according to Olson (1968) primarily dependent on the magnitude of group membership: The greater a group of participating individuals, the less the chance and opportunity turn out to be for providing and maintaining such a good and the greater is the necessity of compulsion, law enforcement, sanctions *etc.*. with respect to usage and distribution of collective goods. Whereas community norms or a morale would still seem satisfactory for reaching a common goal in small groups, this does not apply to large groups. (Buchanan called this phenomenon "the large number dilemma".[5])

The structural problems of social and individual actions, of public goods, and of the commons and social order can easily be illustrated by using the well-known game theoretical model of the so-called *Prisoners' Dilemma (PD)*. A detailed analysis of the PD structure shows that strategic actions of competing self-interested rational agents lead to a result which turns out to be an unintended social consequence putting all participants on a worse level than a cooperative strategy of abiding by social rules would have obtained. PD-constellations cannot be solved on a pure individualistic level.

The above-mentioned dilemmas are also examples of *rationality traps*: the individually rational action strategy leads to collective social irrationality undermining the first one. Under certain conditions, individual rationality can be self-destructive.

The second problem of distributing responsibility does not result from collective corporate action by itself, but only if many act under strategic (competitive) conditions, if negative external, synergistic and/or cumulative effects occur. Indeed, "strategic conditions" means that the final result is dependent on the (relatively independent) acting of many individual agents. Synergistic and cumulative effects would only result, if different components have a joint and mutually escalating impact; the individual components might by themselves be (relatively) harmless, *i.e.* remain under a certain threshoId-value, but yet result in the deterioration or even loss of a highly valued *common good* (think of the example of the continental European forest "dying" from pollution by acid rain and erosion).

3 Naturalists' or Enjoyers' Dilemmas

Earlier (1998, 439f), I dubbed the distribution dilemma regarding the using or enjoying a nature resource or eco-system by different users (*e.g.* fishermen and anglers, hobby sailors, rowers, swimmers, naturalists *etc.*. taking advantage of a lake) "the Naturalists' Dilemma". By contradistinction to the PD, this situation can be pragmatically tackled and the problems solved by dividing and distributing spaces and/or times, certainly *e.g.*, by mutual agreement.

Indeed, there are also *positive variants of Naturalists' Dilemmas*:

"We might easily conceive of a positive variant of the PD which I would like to call *the Naturalists' Dilemma* or, in more general terms, *the Enjoyers' Dilemma* or

Environmentalist's Dilemma with respect to scarce resources. Imagine the only lake in a nature-reserve (*e.g.* in a US National Forest) which is to be enjoyed and partially utilized by anglers and water-skiers at the same time. For the sake of argument the lake should not be that large that both could enjoy their sport at or on the lake without interfering with one another. If both the anglers and the water-skiers would use the lake unrestrictedly they would not to be able to enjoy their sport at or on the lake at all. The water-skier would mingle with the anglers' lines expelling and deterring the fish from the range of the anglers' reach. Thus, they apparently have to come to an agreement with one another in order to be able both to enjoy a nature reserve. They have to arrange for restrictions by, *e.g.* segmenting space or time. They might allot part of the lake to the water-skiers and the other to the anglers or they might for instance allow to water-ski only every second day. Other possibilities of restrictions are conceivable. However, any restriction and segmentation whatsoever would decrease a full-scale enjoyment of both parties. Therefore, the dilemma which arises does not develop from the bargaining of negative sanctions as in the classical PD, but it is a dilemma of the encompassing enjoyment with respect to scarce nature reserves. In this variant, not sanctions of the object of the potential agreement, but the possibility and degree of positively enjoying the natural source or resource are at stake. It is largely the same idea as Hardin (1968) had in mind with the overgrazing of the Sahel zone. The most important difference from the classical PD is that in Enjoyers's Dilemma situations tiered possibilities or levels of opportunities and/or utilisation do occur (by contradistinction to the yes-or-no-strategies involved in the PD model) which admit of variations with regard to degrees or intensity of utilisation or even partially dispensing with them. Here, the pay-offs might be determined - within limits - at will or chosen by steps.

Generally speaking, the mentioned *positive* variant of a Naturalists' Dilemma, the *Enjoyers' Dilemma*, seems to be of considerable interest besides the classical and rather static PD restricted to a bargaining of negative sanctions. The Enjoyers' or Naturalists' Dilemma seems not only to apply to the use of common land or nature reserves, but also to privately owned and exploited land if it is embedded in an endangered ecological environment, because the groundwater level as well as clean air or polluted air, drought and/or soil erosion and depletion would not stop at a conventional borderline, but affect the whole local, regional or even continental ecology.- In the future, more than ever we have to take this problem seriously into account - particularly with regard to nature resources and recreation facilities in the vicinity of cities and larger metropolitan areas of dense population."[6–10]

4 Extended and distributed responsibility and eco-liability

The distribution or, rather, distributability problem of responsibility consists in the fact that side-effects cannot be attributed to a single originator and that they usually are or even could not be foreseen or predicted. We have two partial problems here: First the question of participatory responsibility with respect to cumulative and synergistic harmful effects and second the question how to responsibly deal with unforeseen or even unpredictable facts or side-effects. The first problem can be called the problem of distributing responsibility under strategic conditions. For instance, is the legal principle of attributing "causality" and responsibility valid in Japan indeed satisfactory? It is in force since the case of the *Minamata* disease according to which the statistically assessed contribution to the common harm by relevant polluters in the vicinity is so to speak automatically ascertained by law, as *the* pertaining causality. The burden of proof here lies so to speak on the side of the potential originator as the hypostatized polluter, who has to prove the harmlessness of his emissions. This *reversal of the burden of proof* of the respective attribution seems to be at least a controllable and operational measure to allow for evaluations and distributions wherever environmental damages are in question. In these detriments usually land, water and air use or misuse are combined. They can at least be forestalled or diminished in a controllable way by assigning sanctions. In that respect the Japanese legal principle of attributing causality might foster environmental protection. But there are methodological and legal as well as moral problems connected with such a regulation. First of all, adjacency and the guessing of causality can never be a proof of a causal origin.

In addition, the problem is how to attribute and distribute the responsibility in the cases of synergistic and cumulative damages, particularly those with below-threshold contributions of individual agents. Another problem is how to distinguish between a descriptive assessment of causal origination and the normative attribution of responsibility, between causal responsibility and liability after Hart (1968). How could one possibly distinguish between the causal impact, the descriptive responsibility, *i.e.* the descriptive attribution of responsibility, and the respective normative attribution of responsibility for contributions on the one side – and on the other hand the amount of which subliminal detrimental impact (and how much of it) is individually ineffective, below the threshold of harmfulness? And how is one to *distribute* this kind of responsibility in general? Would it not be meaningful to postulate a normative collective responsibility of all pertinent corporations within the respective region in the sense of a joint liability? This would, however, mean a liability of all relevant corporations for the total damages. The impaired parties could sue for damages, claim in court for compensation and/or indemnification from any presumably participating corporation. Does this make sense, if connected with an overall generalization? This regulation, however, would have the advantage of dispensing with the proof of damage in respect of each singular damaging or aggrieving party. This kind of regulation would, in some way independent of individual case argumentation, interpr*et al*l non-collective agents as quasi one corporative agent being liable in total. The internal distribution and compensation within this quasi-group of corporate agents would then be a problem of mutual bargaining amongst all aggrieving parties.

Notwithstanding these arguments another kind of total liability with respect to product safety and hazards in terms of environmental damages of public goods should be established. It should be noted that there is a European Community agreement as of 1985 with regard to product liability laws. Causal originators of damages would then/now be liable in the sense of a strict liability in tort, whether or not they are really guilty in terms of intent or only negligent. Causal origination would already ascertain descriptive causal action responsibility and with respect to the damage of a good to be protected also normative responsibility for the respective action and its consequences. This form of liability would hopefully be deterrent enough to prevent infringements. If, however, damages would nevertheless occur, it would at least not be necessary to prove fault or guiltiness as a presupposition of any claim for compensation.

Are human beings because of their immense power of technical encroachment and feasibility beyond any beforehand imagination and control now collectively responsible for much more, so to speak, than they could possibly foresee and literally (intentionally) be normatively responsible for? Should they not take over responsibility for unforeseen or even unforeseeable side-effects of their actions with respect to technological and scientific big science projects? But how could they possibly do that? There is no way of really *morally* being held responsible for something one does not know or even could not know. In the sense of *causal* responsibility (descriptive origination) can one be held responsible in some sense, if an unintended damage occurs? The question however is, whether one could be held here responsible in a normative-*moral* sense too. The so-called "principle of causation" if interpreted in a moral and legal sense, would - at least in tendency - adequately engender normative responsibility also. One would have to answer for, to make good for and to be liable for consequences in the sense of being liable to pay compensation *etc.*. The range and power of action seems to have multiplied or grown to such a degree that anticipation cannot follow quickly enough or pursue all the complex ramifications of impacts, consequences and side-effects. This is true notably in our ever-extending complexity of societal and interdisciplinary interactions, be they direct or indirect. That seems to be an intriguing *dilemma of responsibility in our systems technological age*[11] impregnated by *complex systems interactions and dynamic changes* easily transgressing linear thinking and traditional causal disciplinary knowledge. In principle this also pertains to eco-systems and their respective land bases.

5 Distribution Problems of Responsibilities

"The central point with respect to the problem of the distribution of responsibility is the question concerning the normative and descriptive "distributability" in terms of a theory of action and the possibility of adequately reducing the collective responsibility to individual agents in relation to the form of collective actions and causations. Thus, the respective form of a collective action is of determining value and figures as a criterion for the distinction of various attributions of responsibility (see above, chap. 10). Another important point is that the distribution of responsibility is dependent on the kind of responsibility: If one differentiates between a legal liability for compensation and moral responsibility, a distribution is (more) easily attainable and combined with the first kind, while it might be not (so) easy with moral responsibility. In particular, the negative formulations of a responsibility for prevention of damages and the preservation of states of well-being *etc.*. are relevant for the distribution of responsibilities - as is the responsibility to prevent omissions, which is more easily accessible for a regulation of responsibility. One should also differentiate between the sufficient and the necessary conditions of a consequence or damage in relation to several involved persons' failures to act. So, the individual failure to act is causally sufficient for the occurrence of the consequence or damage, if non-omission of the act prevents this occurrence."[6]

Technology, technological progress and economic-industrial development in combination with the respective damages for land, clean air and water turn out to be multi-dimensional phenomena asking for interdisciplinary and complex approaches. The multi-perspectivity is the result of an ongoing mutual interaction between diverse realms and actions of many corporate and individual agents. This is leading to a rather great complexity of individual, collective and corporate contributions, different areas and social background factors. The exponential structure of technological development in terms of range, energy, acceleration, interaction, feedback phenomena *etc.*. is a familiar insight of traditional sociology of science, technology and economic development. This insight is generally true for any multiramified and interdisciplinary interlocking of social phenomena of development.

With regard to responsibility in general, it is not only corporations and institutions in economics and industry which have to bear several sorts of responsibility (see chap. 10), but also the state and its representative decision makers. Corporate responsibility has to be connected with individual responsibilities of the respective representative decision makers. This is true also for big technology projects, particularly if they are run by the state itself. There should be not only a legal, but also a *moral balance* of powers in terms of checks and controls similar to the traditional distribution of power between legislature, government and jurisdiction.

The upshot of this in terms of moral responsibility might be formulated like this: The extension of individualistic responsibility is to be combined with the *development of a socially proportionate co-responsibility*, and with the establishment and analytic as well as institutional elaboration of *social corporate responsibility* (CSR) and a new sensitivity of moral conscience. Types of responsibility would have to be analyzed in a more differentiated way than hitherto (see chap. 10). Only this way we may be able to cope with the most complex structures of causal networks and the far-ranging consequences of human actions and social impacts and interactions of all respective interdisciplinary provenances to a more social orientation of responsibility and even social conscience. Much more attention should be given to that. Ethics and moral philosophy have to take notice of and tackle these new systemic challenges by utilizing the extant technically multiplied possibilities and growing impacts of interactions and system networks in our ever more complex societies.[11,12] An applied ethics of not only collective, but also of strategic and network actions as well as their consequences would seem to be urgently needed indeed.

In the relevant publications the possibilities of a (complete) solution of the mentioned dilemmas are treated with controversy: While some offer rather individualistic propositions others suggest the complementing of institutional, structural or legal and political measures. Not being able to comment on these more closely, we would like only to point out: A moral re-orientation of individuals is necessary, but not sufficient.[13] In addition to a new orientation we need structural incentives, a defusing of situations which threaten to turn into a dilemma, structural changes of the framework, societal mechanisms for sanctioning and institutional legal and political measures. We need to examine a tiered system, a complete set of measures and put them into viable function if possible. This holds true in the same way for the problems in work-situations, which we have only mentioned here. The central question for avoiding social traps is how we can make sure that defection (non-cooperative behaviour) will occur not at all any more (which is highly unlikely). Or not as often as hitherto or at least only to a relatively harmless degree (up to a certain threshold?).

Or, in any case, how may defection be avoided through the help of incentives? The English motto for environmental problems, "Resolution of pollution is dilution" (after 3 SAT, 10.5.1990, on a Sandoz-plant in Cork, Ireland) must and should not be the only solution! We have learned in the last decade that it is no solution at all! Also not the NIMBY-Syndrome ("*Not In My Backyard*")! It should be replaced by some more sophisticated combinations of measures and corporative, collective as well as individual legal *and* moral responsibilities.

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RESEARCH ARTICLE

Decoupling of greenhouse gas emissions from economic growth in Cameroon

Jean Engo

Abstract: Knowledge of decoupling indicators and its determinants is useful for formulating targeted policy recommendations. To this end, the Log-Mean Divisia Index and Tapio models were applied in this paper to study the decoupling relationship among economic growth and GHG emissions in Cameroon over the period 1971-2014. The analyzes were conducted according to the three major periods that marked Cameroon after independence and the decoupling indicators were broken down into seven factors while considering the three main GHGs emitted in this country (*i.e.* CO_2, CH_4, and N_2O). The results showed that weak decoupling, strong decoupling, and strong negative decoupling occurred in Cameroon during the periods 1971-1984 and 1994-2014 which represent the periods before and after the economic crisis, respectively. In addition to these three decoupling statuses, recessive decoupling only appeared during the economic crisis period (1984-1994). From 1971 to 1984 and between 1994 and 2014, carbon intensity, economic activity, population, and emission factor not only contributed to the increase of Cameroon's GHG (particularly CO_2) emissions but also prevented decoupling. Unlike the period 1984-1994, energy intensity contributed to reducing environmental pollution while promoting decoupling during the periods 1971-1984 and 1994-2014. Although all played an important role in decoupling, we found that after the introduction of natural gas into the country's energy mix from 2007, the effect of renewable energies on the mitigation of Cameroon's CO_2 emissions remained higher than the substitution of fossil fuels. However, to develop a cleaner economy, Cameroon should maintain modest economic growth and continuously transform economic development pathways, while encouraging the use of renewable energy to further reduce energy intensity per unit of GDP per capita.

Keywords: Cameroon, economic growth, decoupling, CO_2 emission, energy intensity, greenhouse gas, environmental pollution

1 Introduction

Humanity is facing huge and complex challenges, including environmental degradation, resource scarcity,and climate change.In recent decades, climate change has affected natural and human systems in all regions of the world.[1] These changes, which have been observed since about 1950, are naturally related to human influences and can be summed up in phenomena such as the increase of the number of heavy rainfalls, the decrease of the extremely cold temperatures, the increase of the extremely hot temperatures, and the extreme rise in sea level.[2] Based on the results of several studies, climatologists have pointed out that these climatic effects are mainly caused by a largenumber of greenhouse gases (GHG) currently concentrated in the atmosphere. Global emissions of various GHGs have increased steadily since last century and reached 438 parts per million (ppm) in 2008.[3] This figure was 58% above the pre-industrial level and is close to the 450 ppm threshold, which represents the level associated with a 50% chance of exceeding the overall average temperature variation target of 2°C.[4] Mainly driven by strong demographic and economic growth based on high fossil fuel consumption in developing countries, global GHG concentration is expected to reach about 685 ppm by mid-century and more than 1,000 ppm by 2100.[1,3]

Among the top three GHGsregulated by the Kyoto Protocol, atmospheric concentrations of carbon dioxide (CO_2) which account for more than 70% of the global GHG emission are currently estimated at 403 ppm and are expected to reach about 530 and 780 ppm by 2050 and 2100, respectively.[3,5] Methane (CH_4), which is 25 times more powerful than CO_2 over a 100-year period,

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* **Correspondence to**: Jean Engo, Center for Energy and Environmental Policy, School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China; Email: jean_engo@yahoo.fr

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is the second largest contributor to global warming created by humans. Since the pre-industrial period, the concentration of this gas in the atmosphere has more than doubled, reaching about 1,800 parts per billion (ppb) in recent years and is expected to reach more than 2000 ppb by 2050.[3,6] Nitrous oxide (N_2O) has heat-trapping effects approximately 310 times more potent than CO_2. Over the past 800,000 years, atmospheric concentrations of this gas have rarely exceeded 280 ppb, but since the 1920s they have increased to 328 ppb in 2015 and are expected to reach 350 ppb by 2050.[3,7] One of the worst consequences of these GHG concentration levels is that they would increase the global average temperature from 2.0°C to 2.8°C in the middle of the century and from 3.7°C to 5.6°C at the end of the century[1,3]. Therefore, limiting climate change would require substantial and sustainable reductions in GHG emissions, which, coupled with adaptation, can limit the risks associated with climate change. To this end, more ambitious national climate policies should be put in place to separate GHG emissions from the path of economic growth of developed and developing countries, and in particular, those where industrial emergenciesare expected by 2035 to 2050, like Cameroon.[8]

Cameroon is a country of 475442 square kilometres located in the Congo Basin, specifically between the Gulf of Guinea and Lake Chad.[9] Ten years after its independence, Cameroon's economic development was dominated by oil revenues and its growth increased from 3.09 to 8.06% in 1970 and 1985, respectively.[10] This growth suddenly dropped to 6.77% in 1986 and remained negative between 1987 (-2.14%) and 1993 (-7.93%) due to the economic crisis in the country as a result of falling prices for oil and other commodities in international markets.[10,11] Thanks to huge reforms in economic policy, and despite the devaluation of the CFA franc in 1994,[12] the country's economic growth became positive again and gradually increased from 2.06% in 1994 to 4.03% and 5.92% in 2003 and 2014, respectively.[10] Cameroon's economic growth has slowed in the last three years not only because of the poor global economy but also because of the various security challenges that the country is currently facing along its border with neighboring Nigeria.Meanwhile, Cameroon's population has grown at an average annual growth rate of 2.8% and is currently estimated at over 25 million.[9,10] At the same time, the country's energy consumption increased by 70.87%, from 2.7 to 9.27 Mtoe in 1971 and 2016, respectively.[5,13] This strong energy and economic growth have significantly increased GHG emissions by 34.86%, from 65737.63 to 100922.13 ktCO_2e in 1970and 2012, respectively.Over the same period, the country's CO_2, CH_4 and N_2O emissions also increased by 89.58%, 55.24%,and 55.55%, respectively.[10] As Cameroon's current vision is to reduce its GHG emissions by 32% by 2035,[14] the question of how to decouple GHG emissions from economic growth is currently the most important and urgent issue for this country.

The concept of decoupling was first introduced in environmental studies by (Zhang 2000),[15] to explore the decoupling link between economic growth and carbon emissions in China. The OECD recognized this concept in 2002 as an indicator, which identified two decoupling measurement statuses, namely absolute and relative decoupling.[16] As a result, a series of decoupling surveys were conducted and technological opportunities, as well as increased resource productivity and decoupling, were identified. (Wu, *et al*, 2018)[17] examined decoupling trends in economic growth and CO_2 emissions in typical developed and developing countries over the period 1965-2015, based on decoupling theories. They concluded that developed countries were strongly decoupled and that their stabilization had increased slightly, while developing countries showed a weak decoupling, fluctuating significantly and inconsistently. (Wang, *et al*, 2018)[18] combined the Tapio and LMDI models to compare the decoupling relationship between economic growth and CO_2 emissions from China and the US. They found that China experienced expansive coupling and low decoupling in most years between 2000 and 2014, while the United States experienced mainly weak and strong decoupling. (Dai, *et al*, 2016)[19] also combined the Tapio and LMDI models to study the emergence of decoupling among economic growth and energy-related CO_2 emissions in the BRICS countries between 1995 and 2014. They found that only five states of decoupling appeared among these countries, including weak decoupling, strong decoupling, expansive negative decoupling, expensive coupling, and recessive decoupling. They also concluded that the energy intensity effect played a positive role in reducing CO_2 emissions in the five BRICS countries. Since decoupling is so crucial for sustainable development, many researchers have tried to study decoupling in recent years, including (Engo, 2018; Mikayilov, *et al*, 2018; Zhang, *et al*, 2019; Li, *et al*, 2015; Zhang & Da, 2015).[20–24] The main objective of all this research is to produce effective guidelines and policies to promote economic growth without increasing environmental pressures.

However, we noted that previous studies used CO_2 as a proxy for decoupling economic growth and environmental pollution, and most of them had defined decoupling status only, without exact reasons.Furthermore, in Cameroon, the few studies available on the question of energy-related to environmental pollution such as those of (Tamba, 2017; Noubissi Domguia & Njangang, 2017; Hilaire & Hervé, 2012),[25–27] have only evaluated the causal relationships between environmental, economic, and energy factors. Based on these considerations, the objective of this study is to evaluate the decoupling relationship between economic growth and GHG emissions in Cameroon over the period 1971-2014, based on the Tapio model.The analyzes were carried out according to Cameroon's three major periods of economic development, particularly the period preceding the economic crisis (1971-1984), the period of economic crisis (1984-1994) and the period following the crisis (1994-2014). The study took into account the three main GHGs emitted in Cameroon (*i.e.* CO_2, CH_4, and N_2O) and the decoupling indicators were broken down into seven factors, including the demographic factor, economic activity, renewable energies, energy intensity, carbon intensity, the substitutionof fossil fuel, and the emission factor. With regard to its contribution, this study attempts not only to bridge the gap of previous studies but will also contribute to strengthening the literature in the context of Cameroon. In addition, this study shows the behavior of Cameroon's main drivers of GHG emissions and provides decoupling indicators that can contribute to the policy development needed to achieve the country's GHG emissions mitigation vision. Based on our best knowledge, this study is the first to measure the effect of renewable energies on decoupling.

The rest of this paper is structured as follows. The method used to achieve the objective of this study is presented in section 2. The study's results are presented and discussed in section 3, while we conclude the study in section 4.

2 Methodology and data sources

2.1 Data sources

This study's data cover a 44-year period from 1971 to 2014. Population and GDP data are estimated in millions and billions, respectively, while energy data are estimated in tonnes of oil equivalent (Toe). Data on CO_2 emissions are estimated in tonnes of CO_2 (tCO_2) while those for CH_4 and N_2O are estimated in tonnes of CO_2 equivalent (tCO_2e). All this data was collected from the World Bank and the International Energy Agency.[10, 13]

2.2 Method of decoupling and decomposing GHG emissions

Among all the existing decoupling methods, the one introduced by (Tapio, 2005)[28] from (Vehmas J, Malaska P, Luukkanen J, Kaivo-oja J, Hietanen O, Vinnari M, 2003)[29] works is the most currently used, since he is the founder of the eight logical indicators used in decoupling status definition. According to (Tapio, 2005),[28] the relationship between economic growth and CO_2 emissions can be decoupled using the following model.

$$\omega_{(C,GDP)} = \frac{\%\Delta C}{\%\Delta GDP} \tag{1}$$

where $\omega_{(C,GDP)}$, $\%\Delta$C, $\%\Delta$GDP represents the decoupling index of CO_2 emissions and gross domestic product, percent changes in carbon emissions and percent changes in the gross domestic product, respectively. As one of this study's objectives is to evaluate the decoupling indicators of the three main GHGs emitted in Cameroon, the Equation 1 as follows.

$$\omega_{(GHG_i,GDP)} = \frac{\%\Delta GHG_i}{\%\Delta GDP} = \frac{\frac{GHG_i^t - GHG_i^0}{GHG_i^0}}{\frac{GDP^t - GDP^0}{GDP^0}} \tag{2}$$

where $\omega_{(GHG_i,GDP)}$ and $\%\Delta GHG_i$ are the decoupling index of gas type i (*i.e.* CO_2, CH_2, and N_2O) and the growth rate of this gas between a base year (0) and a target year (t), respectively.After determining the decoupling indicators of these gases based on the Equation 2, we proceed to the identification of decoupling statuses according to the eight logical indicators defined by Tapio as presented in Table 1.

According to Cameroon's second national communication,[30] CO_2 is the most emitted GHG in this country, followed by CH_4 and then N_2O. Based on these indicators and given the lack of data as described in the previous subsection, specific reasons that led to the decoupling status defined by Equation 2 were determined according to the main driving forces of Cameroon's CO_2emissions. To this end, we applied the Logarithmic Mean Divisia Index (LMDI) method, which makes it possible to identify the contributions of a set of factorial variables to the target variable.[31] However, to assess CO_2 emissions at the national level, the Kaya model,[32] whose general form is expressed by Equation 3, is often used.

$$C = POP \times \frac{C}{E} \times \frac{E}{GDP} \times \frac{GDP}{POP} = POP \times CI \times EI \times GD \tag{3}$$

where C, GDP, E, and POP denote total carbon emissions, gross domestic product, energy consumption, and population, respectively.In addition, CI, EI, and GD refer to the carbon intensity per unit of energy used to produce a unit of GDP, energy intensity per unit of GDP per capita

Table 1. The eight logical decoupling status of Tapio

Decoupling statuses		ω(GHG$_i$GDP)	%ΔGDP	%ΔGHG$_i$
Coupling	Expansive coupling (EC)	[0.8; 1.2]	+	+
	Recessive coupling (RC)	[0.8; 1.2]	-	-
Decoupling	Weak decoupling (WD)	[0; 0.8]	+	+
	Strong decoupling (SD)	[- ∞; 0.8]	+	-
	Recessive decoupling (RD)	[0.8; ∞]	-	-
Negative decoupling	Expansive negative decoupling (END)	[1.2; ∞]	+	+
	Weak negative decoupling (WND)	[0; 0.8]	-	-
	Strong negative decoupling (SND)	[- ∞; 0]	+	-

Source: (Tapio 2005)

and economic activity, respectively. The contributions of the factors presented in Equation 3 on Cameroon's CO_2 emissions between the base year (0) and the target year (t) were determined by the following equations:

$$\Delta C_T = C^t - C^0 = \Delta C_{CI} + \Delta C_{EI} + \Delta C_{GD} + \Delta C_{POP} \quad (4)$$

$$\Delta C_{CI} = \sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{CI_i^t}{CI_i^0}\right) \quad (5)$$

$$\Delta C_{EI} = \sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{EI_i^t}{EI_i^0}\right) \quad (6)$$

$$\Delta C_{GD} = \sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{GD_i^t}{GD_i^0}\right) \quad (7)$$

$$\Delta C_{POP} = \sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{POP_i^t}{POP_i^0}\right) \quad (8)$$

Meanwhile, oil, hydropower,and biofuel were the three main sources of Cameroon's energy supply until 2006. Natural gas has been introduced into the country's energy mix since 2007, and currently accounts for 4.82% of total energy supplies, while biofuel, oil, and hydroelectricity account for 69.06, 22.24 and 3.85%, respectively.[10] However, assessing the impact of this government action, which consisted to improve the country's energy efficiency, was also the subject of this study. We sought to understand the behavior of renewable energies and the substitution of fossil fuels effects on CO_2 emissions after introducing natural gas into the country's energy mix.To this end, Kaya's identity (*i.e.* carbon intensity) was expanded in this article,[33] which allowed us to rewrite Equation 3 as follows.

$$C = \frac{C_i}{E_i} \times \frac{E_i}{TF} \times \frac{TF}{E} \times \frac{E}{GDP} \times \frac{GDP}{POP} \times POP = Z \times FI \times RE \times EI \times GD \times POP \quad (9)$$

where C_i, E_i, and TF denote carbon emissions of fossil fuel type (i), fossil fuel consumption of type (i), and total fossil fuels consumption, respectively. f, FI, and RE refer to emission factor, fossil fuel substitution, and renewable energies, respectively.To determine the effects of these factors on Cameroon's CO_2 emissions, particularly over the period 2007-2014, taking into account the available data, the following equations obtained from Equation 9 were applied.

$$\Delta C_T = C^t - C^0 = \Delta C_Z + \Delta C_{FI} + \Delta C_{RE} + C_{EI} + \Delta C_{GD} + \Delta C_{POP} \quad (10)$$

$$\Delta C_Z = \sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{Z_i^t}{Z_i^0}\right) \quad (11)$$

$$\Delta C_{FI} = \sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{FI_i^t}{FI_i^0}\right) \quad (12)$$

$$\Delta C_{RE} = \sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{RE_i^t}{RE_i^0}\right) \quad (13)$$

$$\Delta C_{EI} = \sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{EI_i^t}{EI_i^0}\right) \quad (14)$$

$$\Delta C_{GD} = \sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{GD_i^t}{GD_i^0}\right) \quad (15)$$

$$\Delta C_{POP} = \sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{POP_i^t}{POP_i^0}\right) \quad (16)$$

Meanwhile, to determine the exact reasons for the decoupling status, we applied Equation 4 to Equation 8 and Equation 10 to Equation 15 in Equation 2 to obtain the following equations:

$$\omega_{(C,GDP)} = \frac{GDP^0}{C^0 \times (GDP^t - GDP^0)} \times [\Delta C_{CI} + \Delta C_Z + \Delta C_{FI} + \Delta C_{RE} + \Delta C_{EI} + \Delta C_{GD} + \Delta C_P OP] \quad (17)$$

$$\omega_{CI} = \frac{GDP^0}{C^0 \times (GDP^t - GDP^0)} \times \left[\sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{CI_i^t}{CI_i^0}\right)\right] \quad (18)$$

$$\omega_{Z} = \frac{GDP^0}{C^0 \times (GDP^t - GDP^0)} \times \left[\sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{Z_i^t}{Z_i^0}\right)\right] \quad (19)$$

$$\omega_{FI} = \frac{GDP^0}{C^0 \times (GDP^t - GDP^0)} \times \left[\sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{FI_i^t}{FI_i^0}\right)\right] \quad (20)$$

$$\omega_{RE} = \frac{GDP^0}{C^0 \times (GDP^t - GDP^0)} \times \left[\sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{RE_i^t}{RE_i^0}\right)\right] \quad (21)$$

$$\omega_{EI} = \frac{GDP^0}{C^0 \times (GDP^t - GDP^0)} \times \left[\sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{EI_i^t}{EI_i^0}\right)\right] \quad (22)$$

$$\omega_{GD} = \frac{GDP^0}{C^0 \times (GDP^t - GDP^0)} \times \left[\sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{GD_i^t}{GD_i^0}\right)\right] \quad (23)$$

$$\omega_P OP = \frac{GDP^0}{C^0 \times (GDP^t - GDP^0)} \times \left[\sum_{i=1}^{n} \frac{C_i^t - C_i^0}{lnC_i^t - lnC_i^0} \times ln\left(\frac{POP_i^t}{POP_i^0}\right)\right] \quad (24)$$

where, ΔC_{CI}, ΔC_Z, ΔC_{FI}, ΔC_{RE}, ΔC_{EI}, ΔC_{GD}, and ΔC_{POP} are variables that measure the carbon intensity effect, the emission factor effect, the effect of fossil fuel substitution, the effect of renewable energies, energy intensity effect, the effect of economic activity, and the effect of the population, respectively, on Cameroon's total CO_2 emissions. Similarly, ω_{CI}, ω_Z, ω_{FI}, ω_{RE}, ω_{EI}, ω_{GD}, and ω_{POP} are variables that indicate the effects of each of the previous variables on the decoupling of GHG from Cameroon's economic growth. However, the results of our analyzes are presented and discussed in the following section.

3 Results and discussions

To study the decoupling relationship between GHG emissions and economic growth in Cameroon over the period 1971-2014, we distinguished three main periods and the results obtained for this purpose are as follows.

3.1 Cameroon's decoupling indicators from 1971 to 1984

Table 2 presents the decoupling indicators from the relationship among GHG emissions (including CO_2, CH_4, and N_2O) and economic growth in Cameroon during the period preceding the economic crisis and the devaluation of the CFA franc (1971-1984).

Table 2 shows that the relationship between GHG emissions and economic growth was dominated by a weak decoupling over the period 1971-1984. A strong negative decoupling occurred between 1979 and 1980 for the three gases, and between 1973 and 1974 for CO_2 emissions and from 1975 to 1976 for CH_4 and N_2O emissions; whereas strong decoupling was observed only during the periods 1973-1974, 1977-1978, 1980-1981 and 1973-1975 for N_2O and CH_4 emissions, respectively.These results, in agreement with those of other studies, indicate that Cameroon's economic development

Table 2. Cameroons decoupling indicator during the period before the economic crisis (1971-1984)

Years	ω (CO_2, GDP)	DS*	ω (CH_4, GDP)	DS*	ω (N_2O, GDP)	DS*	%△CO_2	%△CH_4	%△N_2O	%△GDP
1971-1972	9.60E-07	WD**	0.253	WD**	0.285	WD**	0.04	0.006	0.007	0.02
1972-1973	3.19E-07	WD**	0.07	WD**	0.085	WD**	0.03	0.003	0.004	0.05
1973-1974	3.15E-07	SND**	-0.036	SD**	-0.046	SD**	-0.003	-0.003	-0.005	0.1
1974-1975	7.05E-07	WD**	-0.005	SD**	0.053	WD**	0.28	0	0.005	0.11
1975-1976	4.06E-07	WND**	-0.46	SND**	-0.444	SND**	-0.08	0.02	0.02	-0.05
1976-1977	1.15E-06	WD**	0.02	WD**	0.083	WD**	0.43	0.002	0.01	0.13
1977-1978	4.44E-07	WD**	0.114	WD**	-0.046	SD**	0.07	0.02	-0.01	0.22
1978-1979	-5.76E-07	WD**	1.943	WD**	0.286	WD**	0.07	0.11	0.01	0.06
1979-1980	-1.90E-05	SND**	-5.063	SND**	-0.496	SND**	0.08	0.09	0.009	-0.01
1980-1981	1.34E-06	WD**	0.411	WD**	-0.026	SD**	0.05	0.07	-0.004	0.17
1981-1982	1.93E-06	WD**	0.875	WD**	0.316	WD**	0.07	0.06	0.02	0.07
1982-1983	4.66E-07	WD**	42.85	WD**	2.935	WD**	0.08	2.94	0.2	0.06
1983-1984	-8.24E-07	WD**	0.293	WD**	0.093	WD**	0.04	0.02	0.006	0.07

*DS: decoupling status ** See the meaning in Table 1

followed a sustainable environmental security approach during the period 1971-1984.Before 1970, Cameroon's economy revolved around agriculture.Following the discovery of oil deposits throughout the country in the early 1980s, the Cameroonian government implemented policies to restructure its economy.As a result, the shares of agriculture and the tertiary sector in the national GDP decreased from 31 to 21.76%, and from 49.76 to 38.75% between 1971 and 1985, respectively; while that of the industrial sector increased from 19.23% to 37.47%, as shown in Figures 1. This helped to reduce the country's energy intensity per unit of GDP per capita from 0.45 Toe in 1971 to 0.27 Toe in 1984, as shown in Figures 1. Cameroon's economic sustainability and growth thus increased significantly, while dissociating weakly from environmental pollution.

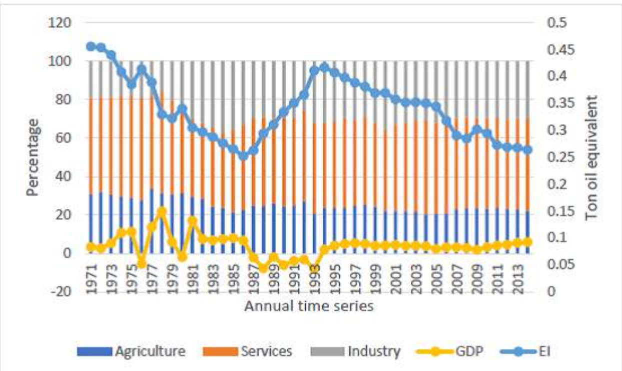

Figure 1. Trends in Cameroon's economic growth and Energy intensity per unit of GDP from 1971 to 2014

Figures 2 and Figures 6 show that energy intensity is the only factor that played an important role in decoupling economic growth from GHG (and more specifically CO_2) emissions over the study period.Although having contributed slightly to increased environmental pollution because of the 1976 economic downturn and the global financial crisis of the 1980s, as shown in Figures 6 during the 1975-1976 (1.77%) and 1979-1980 (2.76%) periods; the total effect of energy intensity had contributed to reducing Cameroon's CO_2 emissions by -27.01% over the period 1971-1984.This finding is consistent with other studies and reflects an improvement in the industrial processes and technologies implemented by Cameroon during this period, which means that the country should continue to promote technologies to reduce its intensity.

In contrast to energy intensity, Figures 6 shows that carbon intensity, followed by economic activity and demographic factors, helped to prevent the decoupling during the period 1971- 1984. Despite the fall observed in 1976 and 1980 as shown in Figures 1, Cameroon's economic growth increased from 3.47% in 1971 to 7.47% in 1984, while the country's population increased from 6697745 to 9742263 over the same period.This strong demographic and economic growth not only helped to increase environmental pollution due to these factors as shown in Figures 6 but also helped to slow decoupling. Figures 6 also shows that economic growth was the main driver of GHG (and more specifically CO_2) emissions over the 1971-1984 period, which indicates that policies aimed at optimizing Cameroon's economic development path should be implemented to promote decoupling.

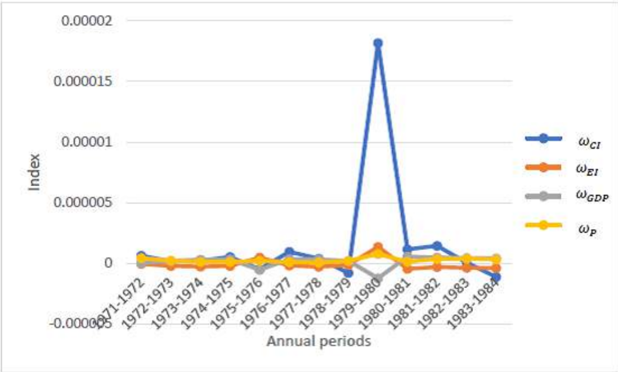

Figure 2. Decomposition of Cameroon's decoupling indicator during the period before the economic crisis (1971-1984)

3.2 Cameroon's decoupling indicators from 1984 to 1994

Caused mainly by the collapse of oil revenues and other commodities on the international markets[11], the economic crisis took hold in Cameroon in 1985, when the country grew by 8% (Figures 1), which was well above that of 1984 (7.47%). During this period of crisis, decoupling indicators derived from the relationship among economic growth and GHG emissions in Cameroon were as follows (See Table 3).

Table 3 shows that the relationship between GHG emissions and economic growth was dominated by a strong negative decoupling over the period 1984-1994, which means that Cameroon's GHG emissions have increased faster than economic growth while destabilizing the quality of the environment. This result, which differs from the majority of decoupling studies, reflects high energy and environmental cost in Cameroon's economic development process during this period and can be explained by the country's economic context at that time. Meanwhile, a weak decoupling occurred during 1984-1986, 1984-1985 and 1993-194, and 1985-1986 periods for N_2O, CO_2, and CH_4 emissions, respectively;whereas strong decoupling was achieved only for CO_2 and CH_4 emissions during the 1984-1985 and 1985-1986 periods, respectively. This result is in line with other studies and indicates that the country's economic growth has been greater than that of GHG emissions, reflecting Cameroon's efforts to judiciously align its resources to ensure good environmental health. Table 3 shows that recessive decoupling dominated the relationship between CO_2 emissions and economic growth, unlike CH_4 and N_2O emissions, where this decoupling status only occurred in the 1986-1987 and 1988-89 and 1991-92 periods; indicating that Cameroon's GHG emissions declined in line with the economic slowdown during those periods. This can be explained by the declining share of the industrial sector in GDP and the increase in energy intensity, as shown in Figures 1.

However, Figures 3 and Figures 7 show that population growth and energy intensity were the main factors that contributed negatively to the development of decoupling in Cameroon during the period 1984-1994. Unlike the period 1984-1986, where energy intensity had contributed to reducing CO_2 emissions because of Cameroon's good economic growth during this period, as shown in Figures 1 and Figures 7, the effect of this factor on environmental pollution were positive and increasing between 1986 and 1994, which also helped to prevent decoupling (See Figures 3 and Table 3). We found that energy intensity contributed to increasing Cameroon's total CO_2 emissions by 38.56% over the period 1984-1994, which is different from the results of other decomposition analysis studiesand can be explained by the high energy consumption (and fossil fuels in particular) that Cameroon has achieved during this complex economic period. Figures 1 shows that Cameroon's energy intensity per unit of GDP rose from 0.25 Toe in 1986 to 0.41 Toe in 1994, reflecting the government's efforts to lift the country out of the economic crisis.Given that the country's population had increased at an average annual growth rate of 3%, from 9,000,345 to 10,456,81 between 1984 and 1994, the State was obliged to increase energy consumption, particularly in the transportation and industry sectors, to respond effectively to the diverse needs of its population. As a result, the demographic factor has contributed to increasing Cameroon's total CO_2 emissions by 39.92%, while helping to prevent the proper development of decoupling.

During 1984-1985, 1987-1989 and 1991-1992 periods, carbon intensity contributed to increasing carbon emissions by 7.84, 219 and 100.31% respectively, while economic activity only contributed to the 18% increase in these emissions between 1984 and 1986, as shown in Figures 7. This is in line with the results of other studies and can be explained by the strong economic growth experienced by Cameroon during these periods. At the same time, the cumulative effects of carbon intensity and economic activity have significantly contributed to reducing Cameroon's total CO_2 emissions by -135.54 and -42.93%, respectively. This means that, with the exception of the above-mentioned periods, these two factors played an important role in promoting decoupling over the period 1984-1994, which is different from previous decoupling studies and can be explained by the context of the country's economic crisis at that time.

Table 3. Cameroons decoupling indicator during the economic crisis period (1984-1994)

Years	ω(CO_2,GDP)	DS*	ω(CH_4,GDP)	DS*	ω(N_2O,GDP)	DS*	%△CO_2	%△CH_4	%△N_2O	%△GDP
1984-1985	5.53E-07	WD**	-1.09	SD**	0.05	WD**	0.11	-0.08	0.004	0.08
1985-1986	-6.20E-06	SD**	6.41	WD**	1.39	WD**	-0.03	0.43	0.09	0.06
1986-1987	6.68E-07	RD**	6.29	RD**	0.74	RD**	-0.007	-0.13	-0.01	-0.02
1987-1988	-4.26E-07	SND**	8.03	SND**	1.34	RD**	0.09	0.62	-0.1	-0.07
1988-1989	-2.46E-05	SND**	54.15	SND**	-6.03	SND**	0.09	0.98	0.1	-0.01
1989-1990	7.16E-06	RD**	-1.11	SND**	-0.61	SND**	-0.02	0.06	0.03	-0.06
1990-1991	1.25E-06	RD**	0.05	RD**	-0.61	SND**	-0.07	-0.001	0.02	-0.03
1991-1992	-7.03E-06	RD**	-0.11	SND**	-0.74	SND**	-0.06	0.003	0.02	-0.03
1992-1993	-1.17E-07	SND**	-0.8	SND**	-0.58	SND**	0.06	0.06	0.04	-0.07
1993-1994	-3.02E-07	WD**	-16.48	WD**	9.32	WD**	0.05	-0.34	0.19	0.02

*DS: decoupling status ** See the meaning in Table 1

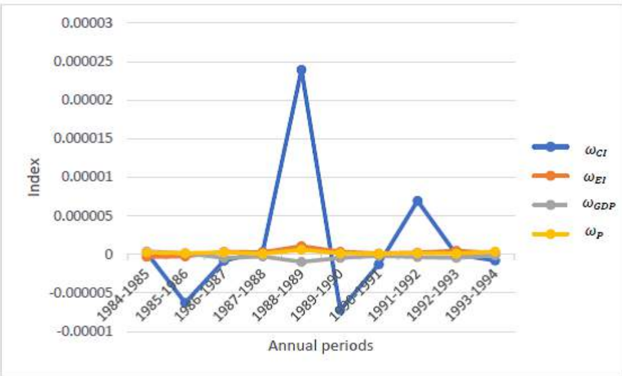

Figure 3. Decomposition of Cameroons decoupling indicator during the economic crisis period (1984-1994)

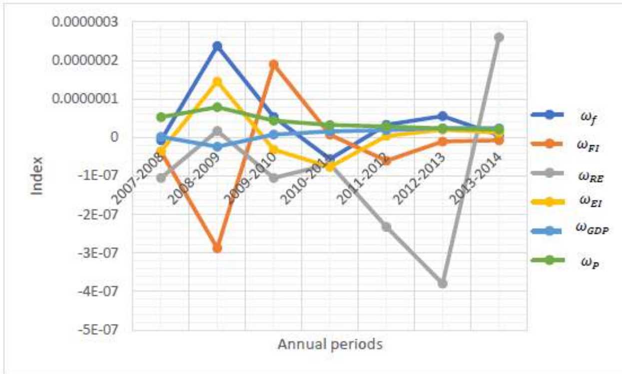

Figure 5. Decomposition of Cameroon's decoupling indicator during the period following the introduction of natural gas into the country's energy mix (2007-2014)

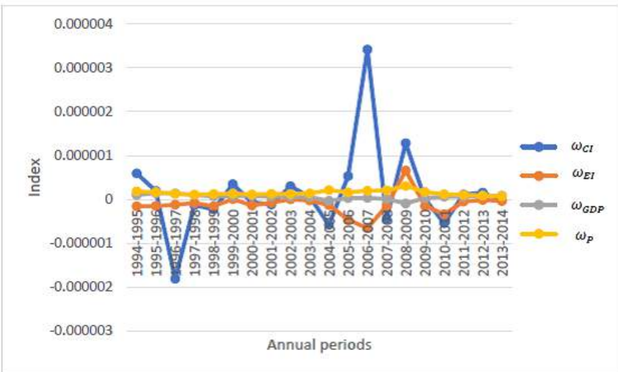

Figure 4. Decomposition of Cameroon's decoupling indicator during the period following the economic crisis and the devaluation of the CFA franc (1994-2014)

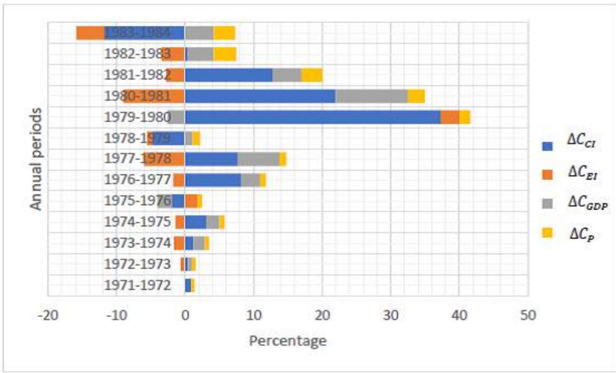

Figure 6. Cumulative decomposition of Cameroon's CO2 emissions during the period before the economic crisis (1971-1984)

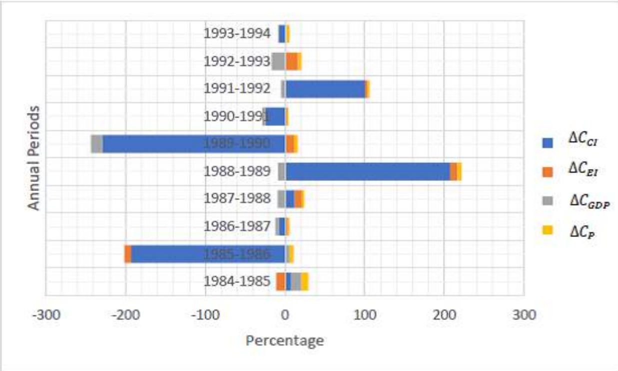

Figure 7. Cumulative decomposition of Cameroon's CO2 emissions during the economic crisis period (1984-1994)

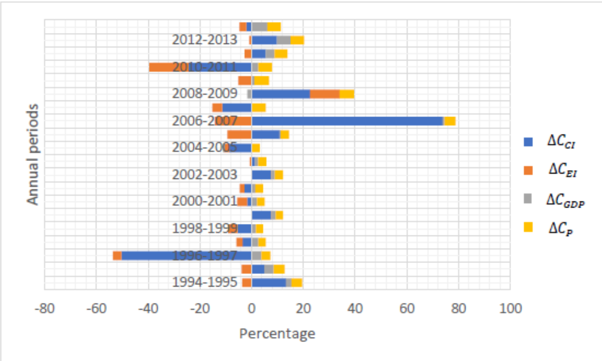

Figure 8. Cumulative decomposition of Cameroon's CO2 emissions during the period following the economic crisis and the devaluation of the CFA franc (1994-2014)

3.3 Cameroon's decoupling indicators from 1994 to 2014

Figures 1 shows that, after being negative between 1987 and 1993, Cameroon's economic growth turned positive again in 1994, reflecting the country's exit from the crisis it had been experiencing for about eight years. Unfortunately, the French Republic devalued the country's currency (the CFA franc) just after it came out of the crisis in 1994.[12] Table 4, therefore, represents decoupling indicators resulting from the relationship among economic growth and GHG emissions in Cameroon following these two unfortunate events.

Table 4 shows that during the period 1994-2008, the relationship between GHG emissions and economic growth was dominated by a weak decoupling, meaning that GHG emissions increased more slowly than economic growth.Unlike CO_2 and N_2O emissions, where strong decoupling was observed only 3 and 2 times, respectively, this decoupling status dominated the relationship among CH_4 emissions and economic growth in Cameroon between 1994 and 2008; which means that

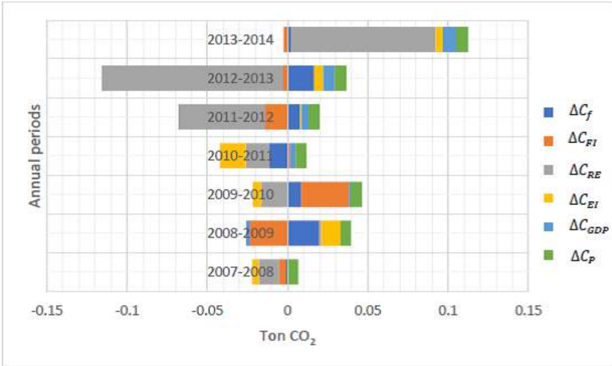

Figure 9. Cumulative decomposition of Cameroon's CO2 emissions during the period following the introduction of natural gas into the country's energy mix (2007-2014)

economic growth increased faster than GHG emissions during these periods.These results are consistent with other studies and show the good economy and environmental sustainability in Cameroon after the crisis.

In order to maintain positive economic growth and less harmful to the environment after the crisis, the Cameroonian government had readjusted its economic and energy policies. As a result, the country's energy intensity per unit of GDP per capita declined from 0.41 Toe in 1994 to 0.26 Toe in 2014, whereas its economic growth increased from 2.06 to 5.92% over the same period, as shown in Figures 1. During this period, the share of agricultural and industrial sectors in the national GDP remained almost stable, while that of the service sector increased due to the emergence of new information and communication technologies.The government has privatized several state-owned enterprises, while others, particularly energy-intensive ones, have seen technological and managerial improvements.Furthermore, several works to improve the country's energy supply have been completed.However, all these actions had not only contributed to reducing energy intensity but also to reduceits effect on Cameroon's total CO_2 emissions by -66.92%.Energy intensity was, therefore, the most important factor in promoting decoupling over the period 1994-2014 (See Figures 4), which is in line with other studies.This suggests that Cameroon should continue to improve technology and energy policy to achieve dynamic decoupling.

Meanwhile, Cameroon's population increased by 41%, from 13109660 in 1994 to 22239904 in 2014, whereas the country's GDP per capita increased from 994.64 to 1293.63 constant 2010 USD during the same period. The immediate consequence of this strong demographic and economic growth is that these two factors contributed to increasing Cameroon's total CO_2 emis-

Table 4. Decomposition of Cameroon's decoupling indicator during the period following the economic crisis and the devaluation of the CFA franc (1994-2014)

Years	ω(CO_2,GDP)	DS*	ω(CH_4,GDP)	DS*	ω(N_2O,GDP)	DS*	%△CO_2	%△CH_4	%△N_2O	%△GDP
1994-1995	7.10E-07	WD**	0.625	WD**	0.27	WD**	-0.03	0.02	0.01	0.04
1995-1996	3.40E-07	WD**	1.369	WD**	0.441	WD**	-0.006	0.06	0.02	0.04
1996-1997	-1.60E-06	WD**	-0.451	SD**	0.31	WD**	0.05	-0.02	0.01	0.05
1997-1998	-9.80E-09	WD**	0.415	WD**	0.423	WD**	0.04	0.02	0.02	0.04
1998-1999	-1.90E-07	SD**	-0.429	SD**	0.26	WD**	-0.1	-0.01	0.01	0.04
1999-2000	5.60E-07	WD**	-0.195	SD**	0.617	WD**	0.16	-0.008	0.02	0.04
2000-2001	-1.30E-08	SD**	-0.059	SD**	0.199	WD**	-0.02	-0.002	0.009	0.04
2001-2002	-5.20E-09	WD**	-1.202	SD**	0.118	WD**	0.06	-0.04	0.004	0.04
2002-2003	4.80E-07	WD**	-0.046	SD**	0.407	WD**	0.03	-0.001	0.01	0.04
2003-2004	2.11E-07	WD**	-1.115	SD**	0.279	WD**	0.01	-0.04	0.01	0.03
2004-2005	-5.30E-07	SD**	-0.328	SD**	0.466	WD**	-0.02	-0.007	0.01	0.02
2005-2006	2.50E-07	WD**	2.174	WD**	-1.847	SD**	0.05	0.07	-0.05	0.03
2006-2007	2.90E-06	WD**	1.909	WD**	2.136	WD**	0.32	0.06	0.06	0.03
2007-2008	-3.80E-07	WD**	1.518	WD**	-0.364	SD**	0.03	0.04	-0.01	0.02
2008-2009	2.15E-06	WD**	-	-	-	-	0.12	-	-	0.01
2009-2010	5.04E-08	WD**	-	-	-	-	0.05	-	-	0.03
2010-2011	-7.07E-07	WD**	-	-	-	-	0.003	-	-	0.04
2011-2012	2.20E-07	WD**	-	-	-	-	0.05	-	-	0.04
2012-2013	3.05E-07	WD**	-	-	-	-	0.09	-	-	0.05
2013-2014	8.90E-08	WD**	-	-	-	-	0.03	-	-	0..05

*DS: decoupling status ** See the meaning in Table 1

sions by 80.29% and 39.69%, respectively. Figures 8 shows that the effects of these factors increased positively throughout the study period, which also made it possible to progressively prevent decoupling, as shown in Figures 4. In addition to these two factors, carbon intensity contributed to increasing Cameroon's total CO_2 emissions by 46.93%, indicating that carbon intensity also played a negative role in decoupling, which is consistent with other studies. Figures 8 shows that carbon intensity contributed significantly to the increase in CO_2 emissions by 73.86 and 22.57% during the 2006-2007 and 2008-2009 periods, respectively; which also led to an increase in the decoupling index for these periods, as shown in Figures 4. This can be attributed to Cameroon's high energy consumption and strong economic growth over these periods.

However, among other measures taken by Cameroon to improve its energy efficiency over the period 1994-2014, we noted the introduction of natural gas into the country's energy mix in 2007. For this purpose, Table 4 shows that between 2007 and 2014, Cameroon's economic development was slightly dissociated from environmental pollution, indicating a low dependence of economic growth on GHG emissions related to energy. Figures 1 shows that over this period, the Cameroonian economy has remained virtually stable at the structural level, which has reduced energy intensity while promoting the achievement of low decoupling.

Figures 9 shows that from 2007 to 2014 renewable energy, fossil fuel substitution and energy intensity contributed to reducing Cameroon's CO_2 emissions by -0.11, -0.01, and -0.001 tCO_2, respectively. These results are consistent with those of other studies and reflect a great technological improvement in different sectors of Cameroon's economic activity during this period.Unlike the transport sector, where oil continues to satisfy all energy needs, we found that the introduction of natural gas into Cameroon's energy mix helped to improve technologies and energy consumption in this country's industrial sector. In addition, despite the fact that the advent of natural gas has contributed to reducing the share of renewable energy in Cameroon's energy mix, significant maintenance work has been done by the government to improve the efficiency of hydropower generation. Therefore, the effects of renewable energy and the substitution of fossil fuels had not only contributed to improving energy intensity and reducing environmental pollution, but also to promoting decoupling in Cameroon, as shown in Figures 5.

Meanwhile, Cameroon's economic and demographic indicators show that the country's GDP per capita increased from 1185.74 constant 2010 USD in 2007 to 1293.63 in 2014 constant 2010 USD, while its population grew by 17.28%, from 18395389 to 22239904 over the same period. Furthermore, Figures 1 shows that the share of the industrial sector in Cameroon's GDP increased from 29.81 to 30%, while that of the tertiary (47%) and agricultural (22%) sectors remained almost stable. These indicators, which reflect high energy consumption, particularly in the industrial and transport sectors due to a sharp increase in urbanization in Cameroon, make it possible to understand from Figures 9 that population, economic activity and emission factor contributed to increasing the country's total CO_2 emissions by 0.047, 0.022 and 0.041 tCO_2, respectively. These results are consistent with previous studies and suggest from Figures 5 that these three factors contributed to preventing decoupling in Cameroon. However, Figures 5 shows that during the 2008-2009 period, the population, emission factor, energy intensity,and renewable energies contributed to increasing the decoupling index, whereas economic activity and substitution of fossil fuels played an important role in this decoupling. This situation can mainly be explained by the slowdown in economic activity experienced by Cameroon at this time, following the unfortunate events experienced by Cameroon in February 2008.[34]

4 Conclusion and policy implications

4.1 Conclusion

This study assesses the decoupling relationship between economic growth and GHG (including CO_2, CH_4, and N_2O) emissions in Cameroon from 1971 to 2014. The analyzes were conducted according to the three major periods that marked Cameroon after independence, namely the period before the economic crisis (1971-1984), the period during the economic crisis (1984-1994) and the period after the economic crisis and the devaluation of the CFA Franc (1994-2014). We used the LMDI and Tapio models to decompose and explore the effects of seven factors in decoupling and the main finding can be summarized as follows.

From 1971 to 1984 and between 1994 and 2014, three decoupling positions, namely strong decoupling, weak decoupling,and strong negative decoupling, emerged in the relationship among economic growth and GHG emissions in Cameroon, indicating that GHG emissions have increased slowerthan economic growth. At the same time, we found that in addition to these three decoupling statuses, recessive decoupling occurred in this relationship between 1984 and 1994, which means that GHG emissions have decreased faster than the economic recession.

However, we found that environmental pollution was higher in Cameroon from 1971 to 1984 than the period 1984-2014 because of the country's strong economic growth at that time. During the 1971-1984 and 1994-2014 periods, carbon intensity, economic activity, population, and emission factor not only contributed to the increase of Cameroon's GHG emissions but also prevented decoupling. During these two periods, energy intensity contributed to reducing environmental pollution by -27.01 and -66.92%, respectively, while promoting decoupling. In contrast to these periods, energy intensity (38.56%) was almost the main driver of CO2 emissions and played a negative role in Cameroon's decoupling process over the period 1984-1994. Meanwhile, the effects of renewable energies and the substitution of fossil fuels have contributed to reducing environmental pollution and promoting decoupling in Cameroon.

4.2 Policy implications

Based on the above results, several policy recommendations to achieve emission reduction targets and to develop a low-carbon economy can be formulated.

This paper shows that scale effects (population and economic activity) had a negative impact on decoupling in Cameroon over the period 1971-2014. To this end, stringent measures should be applied in energy-intensive sectors, such as industry and transport, in order to reduce their impact on the environment. Cameroon should maintain modest economic growth and continuously transform economic development pathways. Various policies should be implemented to encourage high value-added development technologies in secondary and tertiary sectors. Furthermore, the government should promote public transit while increasing publicity and education means to raise awareness of the need for a low-carbon lifestyle.

This study showed that the effects of energy intensity, renewable energies, and substitution of fossil fuels played an important role in decoupling over the period 1971-2014. Therefore, Cameroon's energy structure still needs to be optimized to further reduce energy intensity per unit of GDP per capita in the country. This requires the use of more low-carbon energies, such as natural gas and renewable energies (*i.e.* hydropower, Biomass, wind and solar), which are energy resources available in significant quantities in this country. Cameroon should encourage the development of clean energy technologies such as carbon capture and sequestration (CCS), fuel cell vehicles and biofuels while implementing fiscal policies and subsidies to promote the quality of its environment.

In addition, the State should develop repressive measures aimed at eliminating harmful industries that are not respectful of the country's environmental protection clauses.

Although this study was conducted in the context of Cameroon, its results can serve as a basis for the development of GHG mitigation policies in countries with development conditions similar to those of Cameroon.

5 Acknowledgments

The authors will like to dedicate this work to his family and more particularly to Jeanne Nelly Medou Asso'o, Glorya Engo, and Riskys Engo. Furthermore, we would like to thank the supervisor of this study, Professor Dr. Yi-Ming Wei, in China; and all those who participated in the scientific evaluation of this paper, especially editors and reviewers.

6 Conflict of interest

The authors declare that they have no conflict of interest.

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RESEARCH ARTICLE

Barriers related to the deployment of renewable energies in Cameroon and ways to strengthen policies

Jean Engo

Abstract: Cameroon's current vision is to reduce greenhouse gas emissions by 32% by 2035. To this end, there is no doubt that renewable energies should play the leading role in achieving this goal. This paper applied the fishbone diagram as part of strengths, weaknesses, opportunities, and threats analysis related to the deployment of renewable energies in Cameroon. The results showed that the share of renewable energy in the country's energy mix decreased from 98.9 to 76.11% in 2000 and 2015, respectively. This is due to the decline in hydroelectric generation, which has been caused by the growing share of fossil fuels, with solar, wind and biomass remaining underutilized. Meanwhile, the under-exploitation of Cameroon's energy potential is mainly due to technological, financial, management, and the lack of skills barriers. However, the current rapid development of renewable energy technologies and financial support provided by the International Community under the Paris Agreement are opportunities that Cameroon can seize to engage significantly in R&DV, to promote its energy potential and reduce its dependence on foreign technologies. In this regard, this paper provided some pathways through which policymakers should pay more attention.

Keywords: Cameroon, renewable energy, solar energy, wind energy, biomass energy, hydropower

1 Introduction

According to (IPCC, 2014),[1] global warming is expected to reach 4.8 °C by 2100, and the current humanitarian goal is to keep these temperatures below 2 degrees.[2] To achieve this huge goal, a transition from fossil fuels to renewable energies is required. Currently, about 68% of greenhouse gas emissions are due to energy, and CO_2 accounts for 90% of these emissions.[3] Fossil fuels, which currently account for more than 70% of the world's primary energy supply, remain the most polluting energy source and account for 99% of total CO_2 emissions, of which 34% for oil, 20% for gas natural and 45% for coal[3] . From 1971 to 2015, the share of renewable energies in the world's energy supply increased from 14 to 18%, while that of fossil fuels decreased from 86% to 82% (IEA, 2017)[3] . Thus, if in 44 years the share of renewable energy in the global energy mix has only increased by 4%, it means that the process of transition from fossil to renewable remains ineffective. Although a 4% growth has not been easy for countries that have become significantly involved in this transition process, many remain to be done when we consider that the share of fossil fuels tends to increase in developing countries today.

Over the last four decades, oil has been the main source of satisfaction for global energy needs. The trend has been reversed in recent years in favor of natural gas, whose demand is expected to reach 93 mboe/d in absolute terms by 2040. While annual demand for coal and oil is expected to increase by 0.4% and 0.6% respectively between 2015 and 2040, natural gas demand is expected to increase by 1.8%[4] . This is due to the strong demographic and economic growth of most developing countries, which is now driving growth in gas demand, particularly in the power generation, industry, residential, and commercial sectors. Although the share of fossil fuels in the global energy mix is currently declining, it should be noted that these energies will continue to meet most of the world's energy needs in the future. Therefore, to achieve the goals of the Paris Agreement in a dynamic and effective manner, developing countries should be significantly involved in the process of deploying renewable energies. However, (IEA, 2008; Karytsas & Choropanitis, 2017; McCrone, Moslener, D'Estais, & Grnig, 2017),[5–7] have shown that the deployment of renewable energies remains ineffective be-

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* **Correspondence to**: Jean Engo, Center for Energy and Environmental Policy, School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China; Email: jean_engo@yahoo.fr

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cause of the challenges posed by their implementation across countries. Given the differences in the socio-cultural, politico-economic, environmental, and renewable energy resources that exist between regions or countries, specific knowledge of these challenges in each of these countries or regions is needed. To this end, (Byrnes, Brown, Foster, & Wagner, 2013)[8] have presented these challenges in the case of Australia, (Luthra, Kumar, Garg, & Haleem, 2015)[9] have done in India,[10] in China,[11] in Turkey,[12] in Croatia, and (Kinab & Elkhoury, 2012) in Lebanon.[13] In the same vein as these studies, this paper aims to identify the strengths, weaknesses, opportunities, and threats related to the deployment of renewable energies in Cameroon.

Cameroon's primary energy supply increased by 65.34% between 1971 and 2015, from 2.700.000 to 7.790.000 tonne oil equivalents[3] . Meanwhile, oil, hydroelectric and biofuel were the three main sources of Cameroon's energy supply until 2006. Natural gas has been introduced into the country's energy mix since 2007, and currently accounts for 3.8% of total energy supplies, while biofuel, oil, and hydroelectricity account for 65.50%, 25% and 5.7% respectively[14] . Cameroon's access to electricity increased from 30.06% in 1990 to 56.80% in 2014. During the same period, access to electricity in urban areas increased from 63 to 86.51% and from 13.3 to 22.16% in rural areas[15] . In its vision of emergence by 2035, Cameroon has planned to achieve an overall electrification rate of 75%, with 20% in rural areas[16] . In addition, the country committed to reducing its greenhouse gas emissions by 32% by 2035.[17]

Based on these considerations, it is clear that renewable energy is the most suitable solution for achieving these energy and environmental targets. Therefore, the identification of strengths and weaknesses related to the deployment of renewable energy in Cameroon is required. Knowledge of these barriers is very important for policymakers since they can serve as a basis for formulating effective energy and environmental policies for sustainable development in Cameroon.

The rest of this paper is structured as follows. Cameroon's energy policy is presented in section 2, while the current state of renewable energy development in this country is discussed in section 3. The results of surveys conducted in Cameroon's renewable energy sector are presented and explained in section 4. We conclude the study in section 5.

2 Cameroon energy policy

The development vision of Cameroon's energy sector aims to promote renewable energy and modernize its distribution network in order to respond effectively to domestic demand and export energy to neighboring countries. The main objective of this vision is to reach a total installed capacity of 3000 MW and 5600 MW in 2020 and 2030, respectively. However, Cameroon's energy sector development policies are organized around its long-term energy sector development plan[18] , its strategic poverty reduction paper[19] , its project to extend the electricity network[20] , and its vision for emergence by 2035[16] . Meanwhile, the Cameroonian electricity sector is managed by a set of State agencies whose missions and regulations are recorded in Table 1.[23,24]

3 Resources and current situation of renewable energy in Cameroon

Cameroon's renewable energy policies are organized around the first section of Chapter Two, Title 4 of Law No. 2011/022 of 14 December 2011 governing the electricity sector in the country. This section includes five articles namely Article 63, which specifies the types of renewable energy; Article 64, which defines the nature of renewable energy consumption; Article 65 includes four paragraphs, it defines the management arrangements (production, promotion, R&DV, taxes, and customs); Article 66 includes two paragraphs, it defines the terms of purchase and the involvement of operators in the sector; and Article 67, which stipulates that an agency for the promotion and development of renewable energies may be created in case of need[21] . Meanwhile, Figures 1 shows trends in the share of renewable energies and fossil fuels in Cameroon's total electricity consumption over the period 1999-2015.[15]

We can see from Figures 1 that there is a significant challenge in Cameroon's electricity supply system. In this challenge, it appears that the renewable energy sector is not healthy in Cameroon since 2000. From 1990 to 2001, renewable energies accounted for about 98% of the country's electricity supply, while fossil fuels accounted for 2%. The share of renewable energy suddenly dropped to 74 and 76% in 2007 and 2015, respectively, while that of fossil fuels increased to 25 and 23% during the same period. However, to better understand this growing decline, it is important to look at the different sources of renewable energy in Cameroon.

3.1 Hydropower

As shown in Figures 2[22] , Cameroon is one of the African countries with huge hydropower resources. The country's hydropower potential is estimated at about 23 Gw and is the third largest in the continent after the Democratic Republic of Congo and Ethiopia. The

Table 1. Cameroon legal electricity management framework

Institutions	Assignments	General regulation
Ministry of Water and Energy (MINEE) www.minee.cm	Management of State energy policies	· Law No. 2011/022 of December 14, 2011 Governing Cameroon Electricity Sector · Law No. 2002/004 of 19 April 2002 On Investments in Cameroon · Law No. 2006/012 of 29 December 2006 Setting General Regime of Partnership Contracts
Electricity Development Corporation (EDC) www.edc-cameroon.org	Management of projects related to electricity sector development.	· Law No. 98/022 of 24 December 1998 regulating electricity sector · Law No. 2011/022 of December 14, 2011 Governing Cameroon Electricity Sector
Electricity Sector Regulator Agency (ARSEL) www.arsel-cm.org	Regulating, controlling and monitoring activities of operators in the electricity sector	· Law No. 98/022 of 24 December 1998 regulating electricity sector · Law No. 2011/022 of December 14, 2011 Governing Cameroon Electricity Sector · Decree of 28 June 2013 on the organization and operation of ARSEL
Rural Electricity Agency (REA) www.aer.cm	Management and promotion of rural electrification	· Law No. 98/022 of 24 December 1998 establishing REA · Decree No. 99/193 of 8 September 1999; relating to REA functional organization
The Energy of Cameroon (ENEO) www.eneocameroon.cm	Management of electricity distribution policies	· Law No. 98/022 of 24 December 1998 regulating electricity sector · Decision No. _0096_ / arsel / dg / dcec / sdct du_28 may 2012_ fixing the electricity-free sales tariffs applicable by the company eneo cameroon from the year 2012.

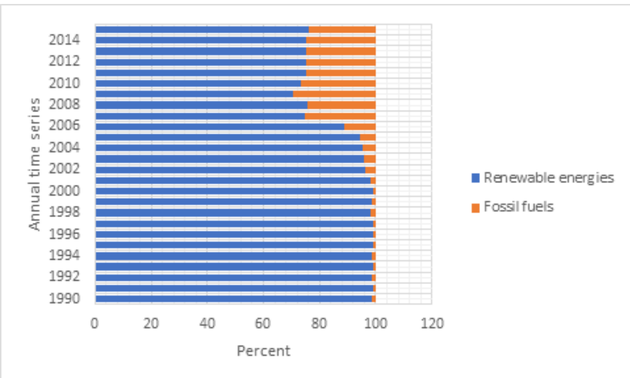

Figure 1. Renewable energy trends in Cameroon's electricity mix between 1990 and 2015

development of this important potential could enable Cameroon to produce more than 115 billion kWh of electricity each year. Unfortunately, only 734 MW of this potential has been developed to date.[22, 23]

Electricity generation from hydro sources is currently provided by three major dams, which account for about 58% of the country's total installed capacity. Among others, we found the Edéa hydroelectric dam (398 MW) acquired in 1952, Song Loulou (264 MW) and Lagdo (72 MW) hydroelectric dams acquired respectively in 1981 and 1982. Next, to these dams, the country has three water retention dams with a total capacity of 7600 million cubic meters, namely Map, Mbakaou, and Bamendjin[23] . Currently, several hydroelectric dams are under construction since 2010, and some of them will be fully operational by 2020 at the latest. These projects are part of Cameroon's vision to increase its actual total installed capacity from 1400 MW to 3000 MW by 2020, and to see more than 5000 MW by 2035. Meanwhile, Figures 3 shows the trend of hydropower in Cameroon's electricity mix over the period 1990-2015[14] .

As shown in Figures 3,[15] hydropower's share of Cameroon's total electricity supply declined from 98% in 1990 to 96 and 73% in 2002 and 2007, respectively. It fell to 72% in 2010 and rebounded to 75% in 2015, a position it had maintained until today. This gradual de-

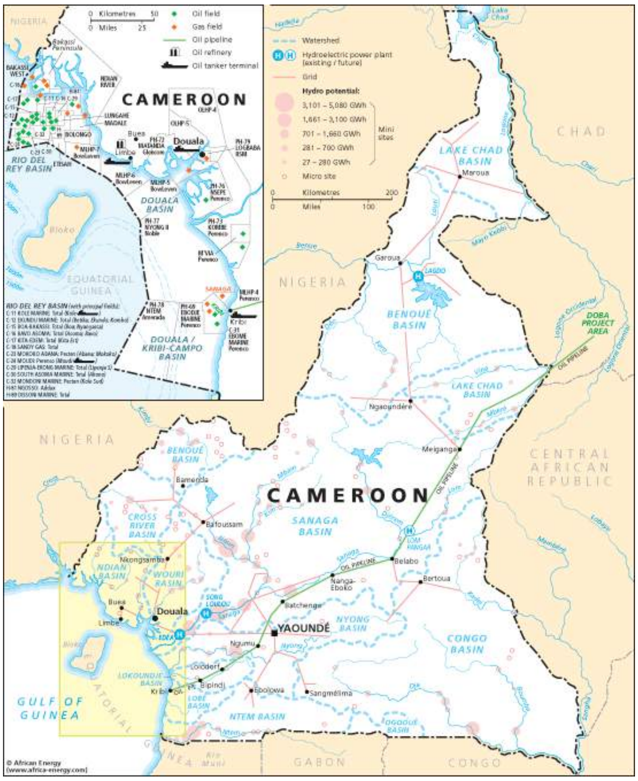

Figure 2. General view of Cameroon's hydropower potential

cline is largely due to the aging of the production equipment since the youngest hydroelectric dam in Cameroon is 36 years old today. In addition, Cameroon's decision to boost energy efficiency through fossil fuels has helped to reduce the effect of hydropower on the country's total electricity supply since 2006, as shown in Figures 1 and Figures 3.

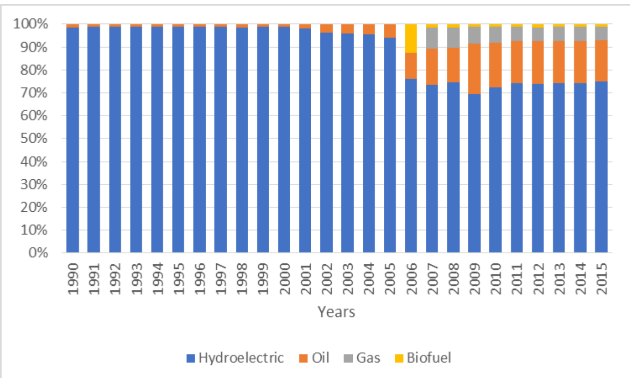

Figure 3. Hydropower trends in Cameroon's electricity mix between 1990 and 2015

3.2 Biomass energy

Cameroon has the third largest biomass potential in sub-Saharan Africa. It is estimated at about 18.8 million hectares of forest[24] , mainly concentrated in the central, southern and eastern regions of the country, as shown in Figures 4.[25]

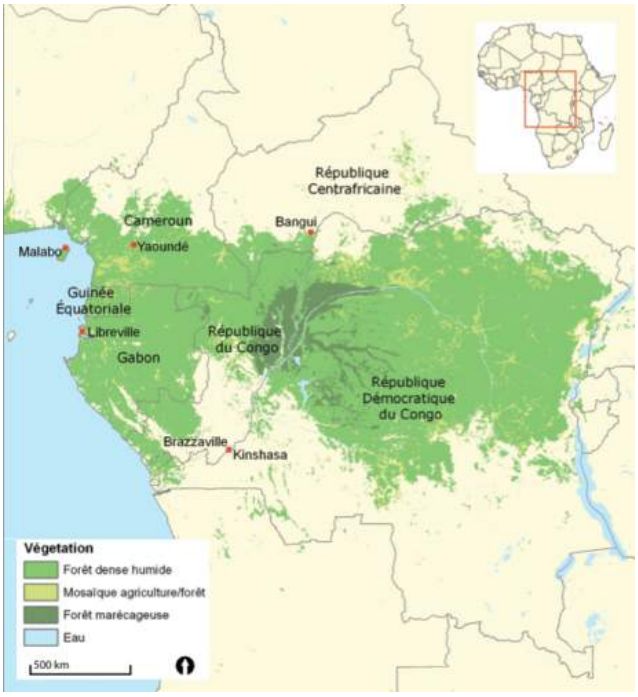

Figure 4. The forest potential of the Congo Basin

Figures 4 shows that biofuel energies have finally received the attention of Cameroon since 2006 when they accounted for 2% of the country's total electricity supply. This share dropped to 1% since 2007 until today, since the marketing of biofuels is not an integral part of Cameroon's energy market and that no effective policy is available to promote this energy. Yet, any significant involvement of Cameroon in the production of biofuels will strongly help to increase the share of renewable energies from this source, given the country's strong production of maize, sugarcane, palm oil, cassava, sunflower, peanuts and inedible plants such as jatropha. Meanwhile, Cameroon is expected to produce 77 million liters of bioethanol and 74 million liters of biodiesel by 2020[26] .

However, deforestation is the main factor currently destroying the Cameroonian forest. Between 1990 and 2015, Cameroon lost 220 000 hectares of forest every year, and even 1% of this forest has never been restored.[24, 27] Three main factors are at the root of this deforestation, namely the rise of global warming, the intensification of agricultural activities and the increase in energy needs. Cameroon is one of the recognized countries highly vulnerable to climate change and more sensitive to any change in temperature due to its geographical location. From 1960 to today, temperatures have risen by about +0.7 degrees Celsius and the country's agro-ecological zones are thus the most affected.[28,29] Currently accounting for about 23% of national GDP, agriculture remains the central pillar of Cameroon's economy. Moreover, apart from importing products such as rice, fish, etc., most of Cameroon's food comes from its land. Similarly, about 90% of Cameroonians currently use firewood, charcoal, and other wastes to meet the energy needs of their household activities such as cooking, heating, lighting, and many others. Therefore, the effects of agriculture and energy consumption on this forest will continue to increase, given the strong demographic growth in Cameroon today.

3.3 Solar and wind energies

After biomass and hydropower, Cameroon also has good potential for solar and wind energy. The country's average solar radiation is estimated at about 4.9 to 5.8 kWh/day/m2 and is more abundant in the north as shown in Figures 5.[24,30] Cameroon average wind speed is estimated at about 2 to 4 meters per second, at a height of about 100 meters. As shown in Figures 6, this potential is abundant in the coastal areas and in the north of the country (5-7 m /s).[30]

Currently, solar and wind energies remain exploited for the satisfaction of primary lighting needs such as solar lamps, recharging the phone's battery, etc. As in the case of biomass, Cameroon's current desire to develop solar and wind energy is strongly linked to the country's vision to reduce its greenhouse gas emissions by 32% by 2035. As part of this vision, Cameroon plans to increase the share of these two energy sources from 0 to 25% in its electricity mix. To this end, solar photovoltaic and wind energy are expected to produce 1345 GWh and 464 GWh of electricity, respectively, in Cameroon by 2035.

However, this paper applied the fishbone diagram and SWOT methods to identify not only the reasons for the under-exploitation of Cameroon's energies sources, as noted above, but also to identify the available opportunities for Cameroon to promote its renewable energies sector. The SWOT (Strengths, Weaknesses, Opportunities, and Threats) method is a strategic analysis tool that combines the study of strengths and weaknesses of an organization, a territory, a sector, etc. with that of opportunities and threats of its environment, in order to provide a development strategy. The purpose of this analysis is to consider both internal and external factors in the strategy, maximizing the potential for strengths and opportunities and minimizing the effects of weaknesses and threats.[31,32] A fishbone diagram method is an analytical tool that helps improve the business management process and is part of quality tools released in 1977 by the Japan

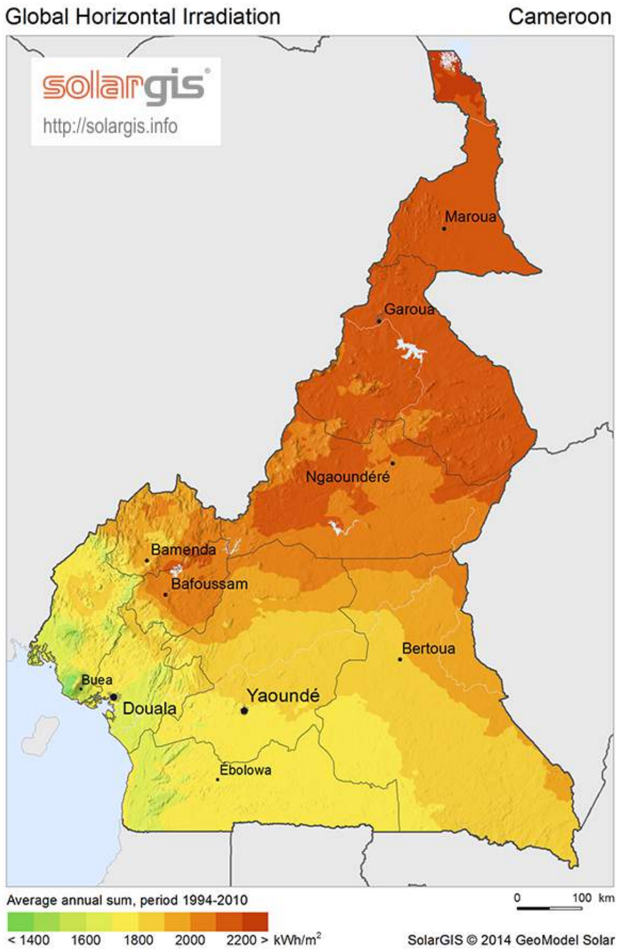

Figure 5. Cameroon's solar energy potential

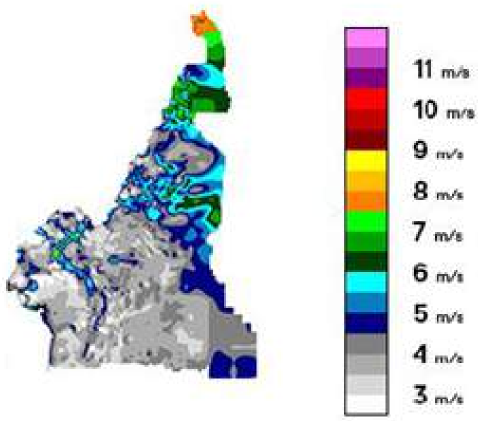

Figure 6. Cameroon's wind energy potential

Union of Scientists and Engineers (JUSE). The principle of this method is to link the causes of a problem to its apparent effect while breaking it down into several sub-problems that are easier to deal with.[33,34] Meanwhile, the results of our investigations based on these two methods are presented in the following section.

4 The SWOT analysis of Cameroon's renewable energy sector

As in most countries in the world and more particularly developing countries, the implementation of renewable energies is subject to several obstacles in Cameroon. Some of these obstacles coincide with those identified in previous studies and others are specifically related to the Cameroonian context, as shown in Table 2 and Figures 7.

Mainly due to technological and financial barriers, Cameroon's renewable energy sources remain very under-exploited. Indeed, the technologies related to the implementation of renewable energies namely, solar photovoltaic, solar heating, wind turbine, and many others, are still very poorly known in Cameroon. Moreover, the country does not have the necessary funding to become significantly involved in the promotion of renewable energy technologies, which means that no project could be easily executed by the State unless it is strongly supported by foreign investment. Meanwhile, Cameroon's willingness to develop its renewable energy potential continues to focus mainly on hydropower. This is not a bad idea if the Government's means allow it to develop only this source of energy. However, the disadvantage related to this energy source lies in the uncertainty of hydroelectric resources availability in the long term. Hence, developed countries tend to develop more solar and wind energy today. The weakness of Cameroon's education system is also one of the biggest problems preventing the deployment of renewable energy in this country. No effort is currently being made to carry out R&D projects, and the country's universities lack a specific training program for renewable energies.

Cameroon's hydropower generation is less efficient today due to the poor state of equipment used in this sector. The majority of these devices are currently very old; they are not adapted to new technologies and lack of effective maintenance. Given the weaknesses mentioned above, equipment related to the efficient development of hydropower, and especially those related to solar energy, wind turbine, etc. are still poorly known in Cameroon. Aside from this material aspect, there is a huge weakness in financial resources. Apart from the fact that it is obliged to deposit about 50% of its revenue in the operating accounts of the French Treasury[35] , under the pretext of guarantee of international exchanges, Cameroon does not have effective financial resources to promote its renewable energies sector. Meanwhile, as currency is a very important factor in terms of trade, the CFA franc is therefore very inefficient on the international markets because it does not allow Cameroon to better express itself on the markets of renewable energy technologies[36] . This calls into question the existing monetary policies between the French Republic and African countries of this CFA Francs zone.

There are several weaknesses in Cameroon's renewable energy management process. Among others, we noted the lack of a management framework appropriate to these energies, lack of this sector sustainable development's vision, administrative slowness, and bad governance. Among other scourges harmful to good governance, there is corruption, bad business climate, massive embezzlement of public funds, mafia networks, lack of alternatives to positions of responsibility, and many others. According to[37] , Cameroon's perceptible corruption index in 2016 was in the 10-19 range, ranking the country 145^{th} out of 176 corrupt countries in the world. In its 2016 report, Doing Business had identified Cameroon as 172^{th} out of 189 countries easy to do business[38] , which does not promote good health of private investment. In terms of management methods, we noted the absence or the inadequacy of a specific legislative framework for this sector, the lack of management policies, and inefficient management processes.

Cameroon is a country of great socio-cultural diversity where currently live more than 24 million people, of which more than 50% are between 20 and 30 years old. This population, native to more than 200 ethnic groups and regularly distributed across the ten regions of the country, can easily communicate in English and French. Meanwhile, about 45% of the Cameroonian population currently lives below the poverty line[38] , and almost 50% of this population still lives in rural areas where about 99% of this 50 % are engaged in farm work. In 2015 Cameroon's HDI value was estimated at 0.518, which placed the country in the low human development category, ranking 153 out of 188 countries and territories[39] . This situation thus reveals the existence of a low standard of living, the lack of effective communication techniques, and above all the lack of skills. At the educational level, about 78% of Cameroonians have completed primary school, and only 13.4% in secondary and 7.7% in higher education of Cameroonians are currently enrolled in technical studies[16] . This reflects the country's inability to carry out the R&DV activities required for the implementation of renewable energy tech-

Table 2. The SWOT matrix of Cameroon's renewable energies sector

	Helpful	Armful
Internal Origin	· The country has a huge desire to boost its renewable energy sector. · Renewable energy potential is available in large quantities. · A large workforce is available across the country. · Natural resources needed for the implementation of renewable energy technologies are available. · The country's working environment is favorable. · People are not against the implementation of renewable energy projects in their localities. · The country is relatively stable politically.	The weaknesses or barriers related to the deployment of renewable energies in Cameroon were analyzed by the fishbone diagram whose results are presented in Figure 7.
External Origin	· The strong growth experienced by renewable energy technologies today. · The gradual decline in the costs of renewable energy technologies. · The financial support of the international community provided for by the Paris Agreement, as regards the countries emitting less greenhouse gases such as Cameroon. · Energy market of the Central African sub region. · Development aid of various origins, *etc.*	· Dependence on foreign technologies · Dependence on foreign investment · Dependence on global economic conditions · Dependence on the effects of climate change · Dependence on the financial security of its international trading partners

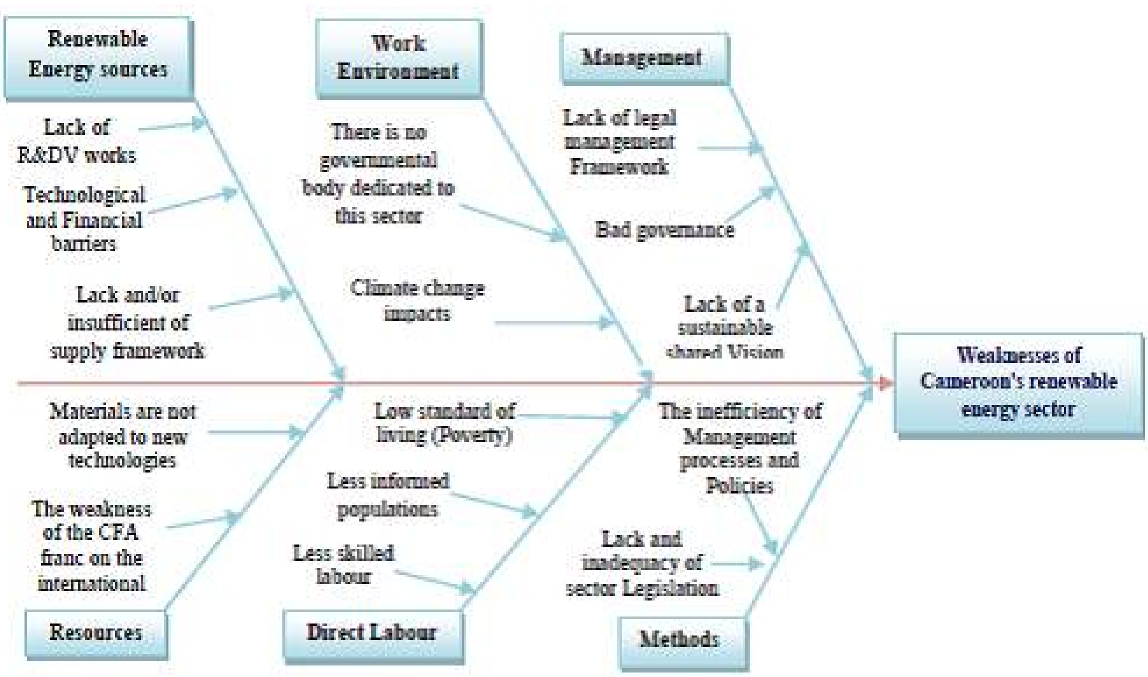

Figure 7. Weakness related to Cameroon's renewable energy sector

nologies.

As shown in Table 1, we noted that there is no specific State agency in charge of the renewable energy sector in Cameroon. Yet, the sustainable promotion of this sector requires the establishment of a physical and moral State's agency, which will deal specifically with issues related to this sector, as is the case in more developed countries than Cameroon. Meanwhile, Cameroon is not spared the adverse effects of climate change that continues to grow in power today. Global warming, floods, landslides, and many others have already marked Cameroon's history on several occasions. Hydropower, which accounted for about 98% of the country's total electricity supply, has continued to become less efficient since 2001, due to the drought of rivers that Cameroon frequently experiences in the first half of each year. This drought, which is mainly due to the increase in temperatures, also contributes to the destruction of the Congo Basin forest, which covers Cameroon in particular. On the security front, Cameroon is one of the African countries that continue to enjoy relatively favorable political stability for development, despite security challenges related to terrorism in the country's border with Nigeria[40] .

5 Conclusion and policy implications

5.1 Conclusion

The main objective of this paper was to identify barriers related to the deployment of renewable energies in Cameroon. To achieve this goal, we applied the fishbone diagram as part of a SWOT analysis to evaluate Cameroon's renewable energy sector. This has not only made it possible to define barriers but also to identify the strengths, threats, and opportunities related to the sustainable development of renewable energies in Cameroon. The results showed that Cameroon has a large potential for underutilized renewable energy, including hydropower, solar power, wind turbines, and biomass. Among other challenges, technological and financial barriers are major problems that prevent the promotion of renewable energies in Cameroon. However, to enable Cameroon not only to achieve its energy and environmental goals but above all to develop a low-carbon economy, policymakers should pay more attention to the following points.

5.2 Policy implications

In terms of renewable energy resources, Cameroon should intensify its hydropower efficiency, while launching significantly in the development of solar, wind, thermal, and many other sources. This would require the development of a technology implementation process strongly rooted in R&DV. Moreover, it would be preferable for Cameroon to further promote the development of solar and wind energy sources, given the uncertainty of the long-term availability of hydropower. To ensure the proper transfer of technology and avoid long-term dependency, Cameroon should reform its education system to enable it to provide the necessary skills for the sustainable development of its renewable energy sector. On the material side, Cameroon should develop a maintenance policy that will promote the rapid implementation of advanced equipment while remaining closely linked to the country's R&DV policy. In addition to these human and material resources, the acquisition of necessary financing for the progressive deployment of renewable energies should constitute a permanent conquest for Cameroon. Thus, given the cost and complexity of access to renewable energy technologies, good planning, and investment choice are required. Meanwhile, Cameroon and all African countries in the CFA Franc zone should review the monetary policies that link them to the French Republic, in order to overcome the weaknesses of this currency in international markets. This initiative will allow these countries and Cameroon in particular, to better express themselves on the international markets for renewable energy technologies. In terms of management, Cameroon should set up a State agency with well-defined missions and responsibilities, which will deal specifically with issues related to its renewable energies. This requires the formulation of dynamic and effective policies and management methods, including a sustainable development's vision of this sector in Cameroon. Meanwhile, Cameroon should intensify and continuously promote good governance practices. This would require eradicating corruption, misappropriation of public funds, mafia networks, etc. The country should also improve its business climate, in order to facilitate the easy penetration of private investment and the innovation of local businesses. However, note that, despite the significant challenges, renewables will remain Cameroon's main source of energy supply, and will further contribute to the development of a low-carbon economy in the future.

6 Conflict of interest

The authors declare no conflict of interest.

7 Acknowledgments

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RESEARCH ARTICLE

Ecologic and economic estimation of land productivity spatial heterogeneity in forest-steppe zone

V.M. Starodubtsev[1*] R.M. Basarab[1]

Abstract: The perspectives of the Sentinel-2 satellite imagery use for the ecological and economic assessment of land productivity spatial heterogeneity in territories with microrelief are analyzed. The duration of microdepressions ("potholes") flooding with melting waters on the winter wheat fields and the resulting decrease in yield have been established. A quantitative determination of the index of heterogeneity of land productivity and its application for the adjustment of the value of agricultural land in the sale and purchase transactions are proposed.

Keywords: land productivity, spatial heterogeneity, microdepression, satellite image

1 Introduction

The ecologic and economic assessment of land productivity spatial heterogeneity attracts scientific and practical interest. It became especially aggravated with the introduction of the so-called "precision farming" into practice, which requires new approaches to knowledge of soils and agricultural technologies for successful competitive farming. And in modern Ukraine, accurate knowledge of the soil cover, expressed quantitatively, is also necessary taking into account the needs of a market economy. After all, the problem of buying and selling the most valuable natural resource of Ukraine land is already overdue.

Previous environmental studies of the spatial heterogeneity problems of the soil cover and land productivity in the Forest-Steppe of Ukraine mainly examined differences in soil lithology, their particle size distribution, organic matter content, agrochemical properties and other features.[1,3] But in fact, here on the flat plains, the soils of microdepressions are formed under the impact of overwetting (and even short-term flooding) with atmospheric precipitation, primarily with meltwater in spring. The distinctive processes in soils of such depressions are, first of all, leaching of carbonates and other products of soil formation, as well as gleying. Agrochemicals and industrial pollutants penetrate with filtered water to a considerable depth (in our case - to groundwater at a depth of 4-5 m) as well.[1,2] And with descending streams of moisture, particles of the solid phase of the soil are also transferred, as a result of which these microdepressions exist for centuries, despite the annual influx of water erosion products into them and even for planning works (leveling the field surface). For the practice of agriculture, the most important consequence of the microdepressions existence in the relief and the spatial heterogeneity of the soil cover caused by them is the heterogeneity of such lands productivity that we study, which affects their value.

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* **Correspondence to**: V.M. Starodubtsev, National University of Life and Environmental Sciences of Ukraine, Kiev, Ukraine; Email: Starodubtsev@voliacable.com
1 National University of Life and Environmental Sciences of Ukraine, Kiev, Ukraine

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2 Materials and methods

The object of research is the formation of land productivity spatial heterogeneity due to the specific water regime of soils in fields with microdepressions in the area of typical chernozem (black soils) of the Right-Bank Forest-Steppe of Ukraine. Experiments were conducted in 2017-2018 in research facilities of NUBiP of Ukraine in the Kiev region. Methodically, they represent the final stage of longer-term studies, including ground-based studies of soil cover on fields with microdepressions (2008-2015), monitoring of the crops condition and soil productivity in 2016-2017, using unmanned aerial vehicles (UAVs), remote sensing of winter wheat sowings with Sentinel 2A and 2B satellites.

3 Results

The critical period for assessing the spatial heterogeneity of the water regime and soil productivity are the first weeks after melting of the snow cover and filling the relief microdepressions with water[1–4] . Therefore, we analyzed images of Sentinel for the period after April 2, 2018, when intensive snow melting began in the fields. The first available image for April 8, 2018 (Figures 1), that is, 6 days after snowmelt, clearly showed the filling with thawed water of deep (50-100 cm) and medium (30-50 cm) relief depressions in a field with winter wheat. And the small depressions (20-30 cm), filled with melt water, turned out to be hardly noticeable due to the general moisture saturation of the surface layer of the soil. The image contrast increased dramatically in the image for April 18, 2018 (Figures 1, in the middle), that is, 16 days after snow melt, when the soil began to dry in even areas of the field.

The deep depressions at that time were filled with water, in the middle depressions the melt water was still on their bottoms, and the shallow ones differed in greater soil moisture compared to even areas. Subsequently, water was consumed for evaporation from the surface, filtration deep into the soil, and for transpiration by preserved wheat plants. After 3 weeks with no rains, melt water was observed only at the bottom of the deepest depressions, and after 4 weeks (Fig. 1, below) it was no longer on the soil surface[1–4] . But in the deep depressions, the wheat plants were already dead or were severely depressed.

Observations in the previous (2017) year on a field with winter wheat also confirmed that melt water remains on the surface of soils in shallow relief depressions for approximately 1 week, in medium (2 weeks), and in deep ones (3 weeks), maximum (4 weeks). This is well illustrated by images[1,3] made by a quadrocopter (UAV) on the second day after intense snowmelt (Figures 2) and after 3 weeks (Figures 3).

To assess the impact of microdepressions flooding with meltwater on the state of winter wheat plants in April 2018, the NDVI index was also determined, showing the spatial distribution of plant mass in the field. In the deepest depressions during prolonged flooding, the plant mass decreased to 5–30% in comparison with even areas. And in the remaining parts of the field, the inhibition of wheat shoots weakened with a decrease in the depth and duration of flooding. Later on, during the growing season, the development of wheat plants was partially restored, but the plants on the bottom and slopes of the depressions ripened more slowly and the grain remained immature for harvesting.

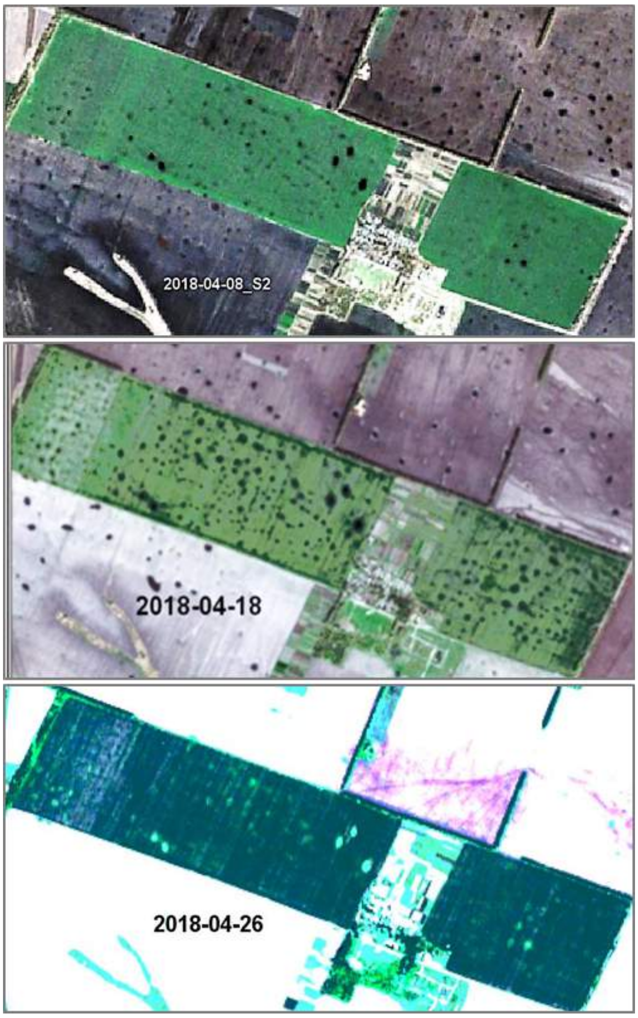

Figure 1. Sentinel-2 images of the experimental field for April 8 (above), April 18 (in the middle) and April 26, 2018 (below)

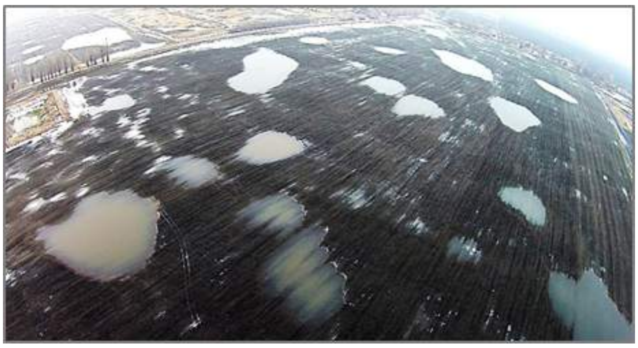

Figure 2. Flooding of microdepressions with melt water on a field with shoots of winter wheat on April 2, 2017

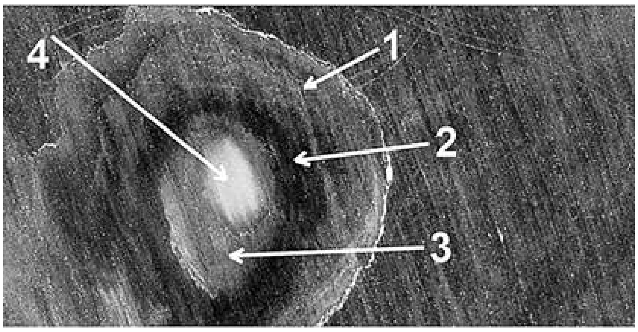

Figure 3. The effect of the duration in the winter wheat flooding by meltwater in the microdepression: 1. weak depression after 1 week of flooding; 2. moderate depression after 2 weeks; 3. severe depression after 3 weeks of flooding; 4. water at the bottom of the depression

In order to assess the real losses of the winter wheat crop in micro-depressions of the relief, the crop was counted using the meter method in 4-8 replications. In our previous study,[4] in deep depressions (50-100 cm), the crop averaged 33% of the yield in flat areas of the field (control), in medium depressions (30-50 cm) with 71%, and in shallow (20 -30 cm) with 84%. In general, the "shortage" (decrease) of the crop in the fields with microdepression was (Figures 4)

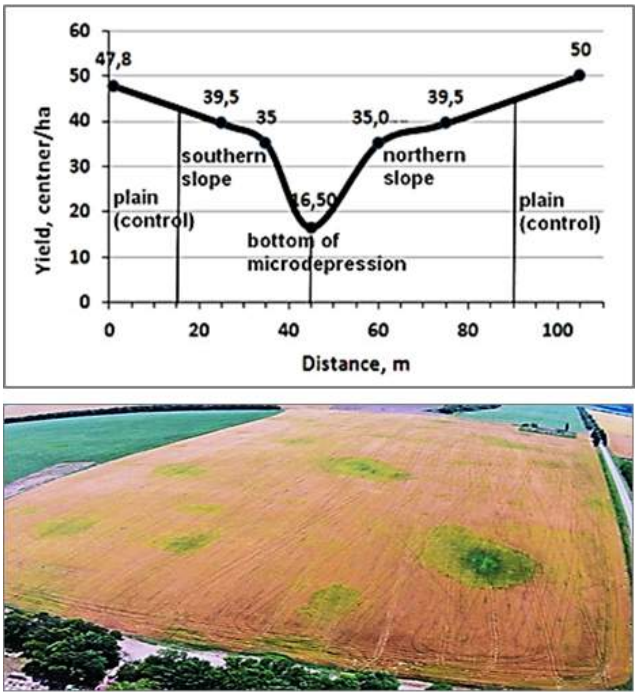

Figure 4. Wheat crop in microdepression and general view of the field before harvesting

Taking into account the obtained results the necessity and possibility of determining and mapping areas of microdepressions with different depths in the fields of the Right-Bank Forest-Steppe with chernozem soils became very important. For this purpose, it was proposed to analyze Sentinel-2 satellite images of the fields with winter wheat crops no later than 2 weeks after the start of intensive snowmelt. Such an analysis (Figures 5) made it possible to determine the areas of microdepressions of different depths in the field under study.

On the area of 180 hectares, deep depressions (50-100 cm) occupy 19.2 hectares or 10.7%, medium (30-50 cm) with 31.8 hectares or 17.7%, and shallow (20-30 cm) with 44.2 hectares or 24.6%.

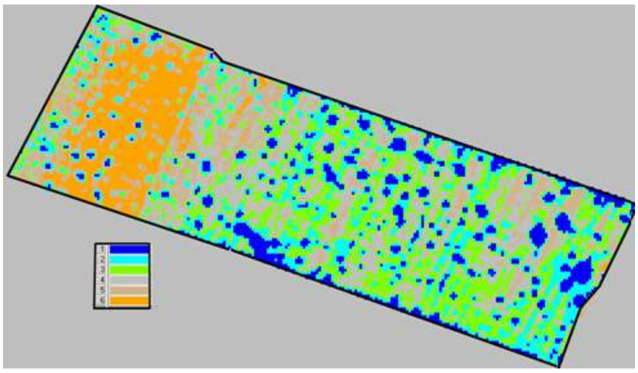

Figure 5. Classification of the relief microdepressions on the field under study with the ERDAS imagine program: 1. deep depressions (50-100 cm); 2. medium (30-50 cm); 3. shallow (20-30 cm); 4-6. relatively flat sections

The data obtained allow us to calculate the proposed **"field heterogeneity index"** according to the microrelief conditions (Equation 1):

$$\mathbf{I_{hf}} = \frac{\mathbf{S_{md}}}{\mathbf{S_f}} \tag{1}$$

where: $\mathbf{I}_{hf}$: index of field heterogeneity; $\mathbf{S}_{md}$: micro depressions area; $\mathbf{S}_f$: total field area.

In this area, the field heterogeneity index was 0.53, that is, 53% of the area is occupied by microdepressions with different depths, and only 47% is occupied by a flat area where there is no spring flooding with melt water and a corresponding decrease in winter wheat yields. We consider it expedient to draw up maps of field heterogeneity, reflecting spatial heterogeneity of land productivity in the area of growing winter wheat. And taking into account the results of our studies of microdepressions' soil[1] in fields with a predominance of typical chernozem, we propose to calculate the "**soil cover heterogeneity index**" according to the formula (Equation 2):

$$\mathbf{Ihs} = \frac{\mathbf{Sps}}{\mathbf{Sts}} \tag{2}$$

where: **Ihs**: index of the soil cover heterogeneity; **Sps** - area of the prevailing soil; **Sts** - total field area.

Naturally, as empirical data are accumulated, the calculation of both indicators will be further improved, taking into account the share "weight" of the components included in **Smd** and **Sts**.

The results obtained also make it possible to calculate the real soil productivity of flat land plots in fields with pronounced microrelief, when production data are available on gross grain yield and average yield. In such cases, it is recommended to do the calculation using Equation 3:

$$\mathrm{Yf} = \frac{Yp \times (S1 \times \mathrm{K1} + \mathrm{S2} \times \mathrm{K2} + \mathrm{S3} \times \mathrm{K3} + \mathrm{K4} \times \mathrm{S4})}{(S1 + S2 + S3 + S4)} \quad (3)$$

where: **Yf**: actual average yield**Yp**: yield of flat areas; **S1, S2, S3, S4**: areas of flat plots, shallow, medium and deep depressions; **K1, K2, K3, K4**: yield reduction ratios: (K1 = 1.00; K2 = 0.84; K3 = 0.71; K4 = 0.33).

In the field under study, where winter wheat was grown in 2018 using the bacterial fertilizer Extrakon, which was developed and introduced by Professor Patyka NV, the average yield was 71 centners per hectare. The calculation by the proposed equation allows us to determine that the real yield on flat plots was 84.1 centners per hectare, that is, 13.1 centners per hectare more. And in shallow micro-depressions of the relief, it was 70.6 centners per hectare, in medium (59.7 centners per hectare, and in the deep ones (only 27.7 centners per hectare). Consequently, due to the peculiarities of the water regime of the soil, micro-depressions in this field alone collected 236 tons of wheat less than would be potentially possible in accordance with the effective fertility of chernozem soils. In general, for farms of Right-Bank Ukraine, this factor is very significant and should be taken into account when determining the price of land, depending on the quantitative assessment of the microdepressions of the relief presence on specific fields. And in the mapping of the lands of this region in accordance with the index of spatial heterogeneity of their productivity, the authors are ready to assist farms on a contractual basis.

4 Conclusions

(1) Satellite images of Sentinel-2a and 2b are promising for assessing the spatial heterogeneity of land productivity with well-marked microrelief.

(2) The optimal time for these satellites to probe the surface of fields with winter wheat sowing is 2 weeks after the onset of intense snowmelt and flooding of microdepressions with melt water.

(3) Joint ground-based, airborne (UAV) studies and remote sensing determined the average duration of flooding with melt water in micro-depressions with winter wheat crops, depending on their depth: shallow depressions (20-30 cm) flooded on average for 1 week, medium (30- 50 cm) with 2 weeks, deep (50-100 cm) with 3 weeks.

(4) The coefficients of the winter wheat yield decreasing in micro-depressions were determined empirically, taking into account their depth and duration of flooding. The yield total decrease in fields with micro-depressions is estimated at 1.3 t/ha.

(5) The index of spatial heterogeneity of field productivity (Ihf) is proposed for a quantitative assessment of such heterogeneity according to the equation **Ihf = Smd/Sf,** where **Smd** is the area of microdepressions, **Sf** is the total area of the field.

(6) To assess the complexity of the soil cover of fields with microdepressions, a calculation of the "soil heterogeneity index" **(Ihs)** was proposed at a certain taxonomic level of soil classification: **Ihs = Sps/Sts**, where **Sps** is the area of prevailing soil, **Sts** is the total area of the field.

(7) A method is proposed for estimating wheat yield in micro-depressions with different depths according to the average yield determined from the gross grain harvest and empirical coefficients of yield reduction in them (Equation 3).

(8) It is recommended to use the "productivity spatial heterogeneity index of the field" to adjust the price of agricultural land for the sale and purchase. To do this, it is advisable to carry out mapping of the flat areas of the Forest-Steppe of Ukraine according to this indicator.

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#09-04 Thong Chai Bldg
Singapore 169874
Tel : (+65) 68264112; (+65)98107233
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