JICA Research Institute

JICA-RI Working Paper

Applicability of Multi-Agent Simulation (MAS) on International Development Issues

Conflict Analysis in Virtual States (CAVS): A New Experimental Method Based on the Extensive Use of Multi-Agent Simulation (MAS) and Geographical Information System (GIS)

Takuto Sakamoto

No. 56

March 2013

JICA Research Institute

JICA Research Institute

JICA Research Institute
10-5 Ichigaya Honmura-cho
Shinjuku-ku
Tokyo 162-8433, JAPAN
TEL: +81-3-3269-3374
FAX: +81-3-3269-2054

Conflict Analysis in Virtual States (CAVS): A New Experimental Method Based on the Extensive Use of Multi-Agent Simulation (MAS) and Geographical Information System (GIS)

Takuto Sakamoto*

Abstract

Conflict Analysis in Virtual States (CAVS) offers a fresh approach to analyzing civil conflicts, which also has significant potential for policy application. This approach, made possible by the use of two computer-based methods comprising multi-agent simulation (MAS) and a geographical information system (GIS), basically consists of observing and analyzing simulated dynamics of civil conflicts. Characteristically, these simulations are run in 'realistic virtual states,' which are constructed virtually but reflect some of the defining characteristics of corresponding sovereign states that exist in the real world. In short, controlled pseudo-experiments concerning civil conflicts are conducted in a virtual environment that sufficiently approximates the empirical reality.

This working paper introduces CAVS and reports on its latest developments.

First, the paper gives an overview of CAVS and its two major components: a MAS model of virtual states and GIS datasets on actual states (e.g., demographic distribution, distribution of ethnic groups, etc.). This overview is followed by some illustrative examples of simulation runs conducted in several virtual states that approximate existing states in Northeast Africa (Eritrea, Ethiopia, Kenya, Somalia, and the Sudan).

The paper then details the substantial improvement and extension that the CAVS platform is now undergoing. This ongoing development includes: restructuring and unification of the GIS datasets; introduction of a much-strengthened and more flexible interface between the GIS data and the MAS model; and a substantial extension of the MAS model itself, particularly in its coverage of international and transnational factors.

Lastly, the paper describes several research projects currently underway, such as investigations into the effects on civil conflicts of a variety of external influences and interventions. Firmly based on the extended CAVS platform, these projects have clear policy implications.

Keywords: civil conflicts, Africa, multi-agent (agent-based) simulation (MAS), geographical information system (GIS), policy experiments

* Research Associate, Department of Advanced International and Social Studies, Graduate School of Arts and Sciences, University of Tokyo (sakamoto@waka.c.u-tokyo.ac.jp)

JSPS KAKENHI (Grant Number 15GS0102, 24243023 and 24730139) provided financial support during the preparation of this paper.

1. Introduction

Whether in academic or practical terms, dealing with civil conflicts has always been a challenging task. The daunting and urgent nature of this task requires powerful intellectual equipment on the part of both researchers and practitioners: equipment that enables them to clarify the complex mechanisms of conflicts as well as to examine various policy interventions for effectively managing these conflicts.

This paper introduces a novel approach that can considerably strengthen such equipment. The approach, called Conflict Analysis in Virtual States (CAVS), basically consists of observing and analyzing simulated dynamics of civil conflicts. Characteristically, these simulations are run in 'realistic virtual states,' which are constructed virtually but reflect some of the defining characteristics of the corresponding sovereign states that exist in the actual world. In short, one conducts controlled pseudo-experiments concerning civil conflicts in the virtual environment that sufficiently approximates the empirical reality.

This approach is made possible by two computer-based methods: multi-agent simulation (MAS) and a geographical information system (GIS). The former offers a way to explicitly model and analyze complex interactions among a large group of autonomous agents, while the latter provides a comprehensive platform for constructing and managing a variety of geo-spatial data. Both methods have shown rapid development and wide application in the past two decades.

Based on the integrative use of these two methods, CAVS has huge potential, especially for policy application. The following describes CAVS and its ongoing development along with some of the related projects currently underway.

2. Background

The past two decades has seen exponential growth in the volume of academic research on civil conflicts. Yet, in terms of practical applicability and policy implications, which largely concern the present paper, the literature is quite unsatisfactory. For any focused policy responses to diverse conflict situations should be based on a context-sensitive understanding of conflicts: an understanding that offers knowledge and information meaningful enough in each particular situation at hand. Apart from a large amount of (often too specific) case studies, however, many studies on 'onset,' 'duration' or 'termination' of conflicts are too general and/or too aggregated to enable such an understanding.

The literature is too general because theories are constructed in highly abstract, often utterly unrealistic settings. For instance, the dominant modeling approach, whether it relies on concepts like 'security dilemma' and 'credible commitment' (Posen 1993; Snyder and Jervice 1999; Walter 1997, 1999), or it employs more formal tools like game theory (e.g., Fearon 1998, 2004), treats a conflict as something coming from strategic interaction among a few (mostly two) groups that are more or less constant and monolithic. Many of the dynamic and fluid elements observed in the actual conflict situations, including the group formation and dissolution process, are simply beyond the reach of such a stylized and static framework. This makes the framework largely irrelevant for many specific cases of conflict.

The conflict literature is also too aggregated because theories are tested against empirical data that are mostly collected at the national level. Cases in point are the major large-N analyses that have caused much controversy among researchers. The propositions that cast doubt on the empirical relevance of ethnic fractionalization/polarization or socio-economic inequality in explaining occurrence of conflict, for example, are based on the statistical insignificance of the proxies employed such as the Ethno-Linguistic Fractionalization index (ELF) and the national GINI coefficient (Collier and Hoeffler 2004;

Fearon and Laitin 2003; Hegre, Gissinger, and Gleditsch 2003). These indexes are calculated and aggregated at the national level, while conflict events and their possible covariates most often show considerable sub-national spatial variation over the state territory.

Fortunately, these problems are now being addressed with the growing focus on 'disaggregation' of conflicts. The most conspicuous development in this regard is the more explicit treatment of space and geography, as the increasing use of GIS data in empirical analyses of civil conflicts indicates (e.g., Cunningham and Weidmann 2010; Østby Nordås and Rød 2009; Weidmann, Rød, and Cederman 2010). These spatially more disaggregated analyses often lead to conclusions considerably different from the ones that were obtained in the previous analyses. Moreover, there have been an increasing number of theoretical models that analyze civil conflicts in a spatially as well as temporally disaggregated manner (Cederman 1997, 2008; Weidmann 2006; Weidmann, Hegre, and Raleigh 2006). Employing MAS due to the sheer amount of interactions involved, these models variously simulate conflict dynamics along with the accompanying process of group formation and dissolution in a virtual space.

In short, emerging techniques like GIS and MAS offer a fresh opportunity for a much more focused understanding of civil conflicts than the preceding approaches have allowed. Particularly, the combined use of these methods can be effective because it enables more dynamic as well as contextual treatment of conflicts. Several of the most recent contributions have indeed been pursuing such a line of research (Bhavnani and Choi 2012; Cederman and Girardin 2006; Lim, Metzler and Bar-Yam 2007; Weidmann and Sulayen [Forthcoming]). These works conduct MAS of civil conflict in a realistic virtual environment that, with the aid of GIS, mirrors the actual geo-spatial makeup of the country or its part in question. Bhavnani and Choi (2012)'s simulation of civilian violence in 'Virtual Afghanistan,' and Weidmann and Sulayen (Forthcoming)'s simulation of sectarian clashes in 'Virtual Baghdad' are prominent examples.

CAVS builds on this 'Virtualizations' strand of conflict research (Lustick and Miodownik 2009): By employing both MAS and GIS in an integrative way, it constructs a comprehensive platform for analyzing civil conflicts without losing touch with empirical reality. Furthermore, as is shown below, this platform allows comparative analyses of multiple empirical cases while ensuring a comprehensive grasp of the macro-dynamics of state territorial rule observed in each case of conflict. Both of these features are mostly lacking in the preceding works just mentioned.

3. Model, Data and Basic Results: An Overview[1]

(1) Constructing virtual states

The platform for CAVS is a model that simulates diverse dynamics of state territorial integration and disintegration caused by spatial expansion and recession of civil conflict.[2] This model builds on a set of virtually constructed sovereign states. Each virtual state, which has so far been represented as a separate, self-contained entity without any interaction with other states, has its own territory, government and inhabitants with diverse socio-cultural traits. The model also assumes the existence of a large number of latent insurgent organizations, which are trying to infiltrate the country concerned from randomly determined points on its territory, and to subvert the rule of the central government by force. Around the territory, local competition between the government and insurgents takes place, and sometimes spreads to the surrounding localities. Over time, the parallel processes of such competition lead to various spatial

1. This section basically summarizes the author's preceding research, which has been reported extensively in Sakamoto (2011a; 2013). See these works for more detail.
2. This model is implemented on a multi-purpose simulator called *artisoc* (*art*ificial *soc*iety). *artisoc*, which has been developed and updated by Kozo Keikaku Engineering Inc. (KKE), provides an accessible environment for developing and executing a MAS model with a minimal level of programming skill. Its freeware version, *artisoc player*, on which the model is executable, is available from KKE's web site (http://mas.kke.co.jp/. [in Japanese]). For a comprehensive introduction to *artisoc*, see Yamakage (2009). The model itself can be downloaded from http://citrus.c.u-tokyo.ac.jp/vs/eng/.

dynamics of civil conflicts, driving the overall pattern of territorial integration and disintegration of the country in question in diverse directions.

More specifically, the model consists of two kinds of mutually interacting agents: a *PopCell* agent representing a tract of the territory and inhabitants living there; and a *Ruler* agent representing the central government or one of many insurgent organizations. The former is characterized by the socio-cultural traits of its inhabitants (*Traits* variable) such as ethnicity and religion as well as by the amount of material and human resources (*Resources* variable) that exist on the cell. The latter, on its part, governs *PopCell*s and mobilizes their resources, which are in turn deployed over its territory for military competition with other *Ruler*s. A *Ruler* is also characterized by its traits (*Traits* variable), which indicates its inclination toward inhabitants' socio-cultural traits (e.g., committed to the Arab population, indifferent to any ethnic group, etc.). The model's overall structure, including a list of other variables and parameters in addition to those mentioned above, is summarized in Table 1 (see Sakamoto 2011a, chap.2; 2013, 8-13 for more detail).

Table.1. The Structure of the virtual state model

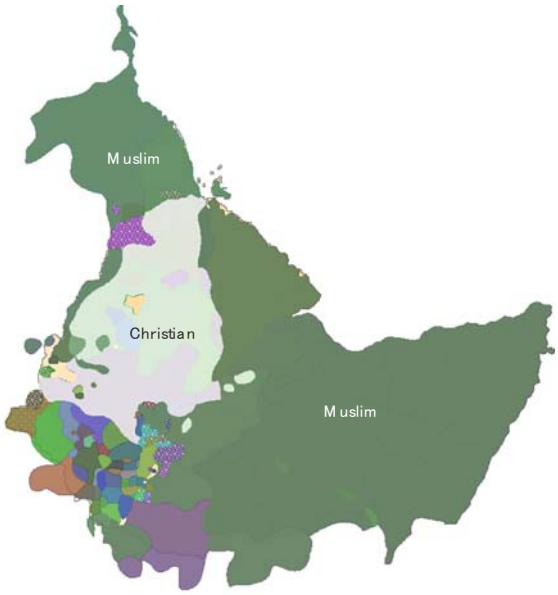
Name	Description	Properties
***PopCell* (Agent)**	Represents a Tract of Territory and its Inhabitants	
–State	Indicates a *Ruler* to Which the Cell Belongs	The Same Value (i.e., Govt.) at First; Endogenously Generated Thereafter
–Traits	Describes Socio-cultural Traits (Ethnicity, Religion, Region) of the Inhabitants	Derived from Empirical Data
–Resources	Denotes the Amount of Resources	Derived from Empirical Data
***Ruler* (Agent)**	Represents Government or Insurgent Organization	
–Traits	Describes Inclination toward Inhabitants' *Traits*	Derived from Empirical Data for Govt.; Randomly Generated for Insurgents
–Mobilization Level	Specifies the Fraction of *PopCell*s' *Resources* to Collect	Exogenously Given for Each
–External Resources	Specifies the Amount of Externally Generated Resources	Exogenously Given for Each
Other Parameters		
–Number of Rulers	Specifies the Total Number of *Ruler* Agents	Exogenously Given
–Coercion Effect	Specifies Relative Strength of Military Coercion in a *PopCell*'s State Transition	Exogenously Given
–Sensitivity to Frontline	Specifies Weight Attached to a 'Frontline' *PopCell* in a *Ruler*'s Deployment of Resources	Exogenously Given
–Stochastic Noise	Specifies the Extent to Which a *PopCell*'s State Transition Depends on Contingency	Exogenously Given

A simulation run starts from the 'initial state' in which a single *Ruler*, that is, the central government, exclusively rules all the *PopCell*s that constitute the virtual state's territory. Such a condition can undergo substantial changes as each *PopCell* changes its affiliation with *Ruler* agents (*State* variable of the *PopCell*) through local interactions among the agents. These interactions occur according to fairly simple logics of military and political behavior: put simply, a *PopCell* tends to come under the rule of an adjacent *Ruler* that is militarily resourceful as well as politically inclined toward the inhabitants on that cell. Based on the MAS

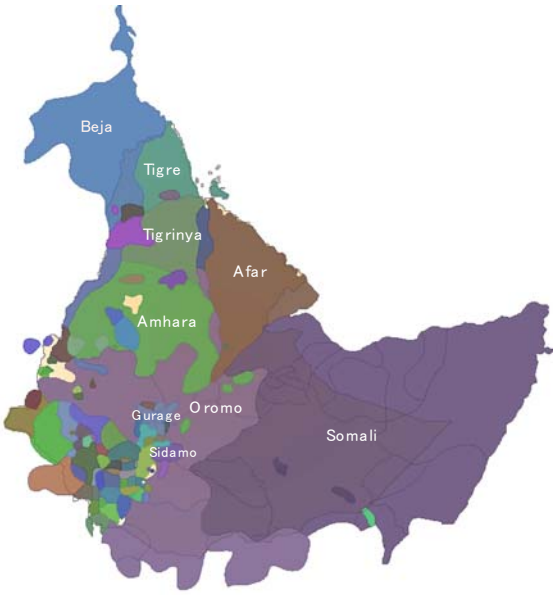
technique, such micro-logics dynamically generate successive macro-states of conflict and integration/disintegration over the territory of the virtual state concerned. More precisely, one observes, as the main output of a simulation run, a time-series succession of spatial configurations of the *PopCell*s' *State* variables, which represents changing phases of territorial division among the competing *Ruler*s.

As is mentioned above, in CAVS, each virtual state has its 'counterpart' in the actual world: it is firmly connected with one of the existing sovereign states in reality. GIS and other empirical data ensure such a connection. For example, the *Traits* variables of *PopCell*s in a virtual state are determined on the basis of GIS datasets on the spatial configurations of ethnic groups, religious groups and regional units in the corresponding country (see Fig. 1). Similarly, the *Resources* variable of each *PopCell* is derived from spatial data on the population distribution of the country concerned (see Fig. 2). More specifically, it is assigned a specific value that is the product of the local population count and the aggregate GNI per capita at the national level. Of the GIS datasets employed in CAVS, those on the socio-cultural traits were constructed by the author himself, who consulted several data sources (e.g., Asher and Moseley 1993). The data on demographic distribution, on the other hand, are from the existing dataset (CIESIN, Columbia University and CIAT 2004). The exhaustive list of the empirical datasets employed along with their respective sources is given in Table 2 (see also Sakamoto 2011a, chap.3).

Fig.1. Examples of trait distributions



Ethiopia-Eritrea: Ethnicity



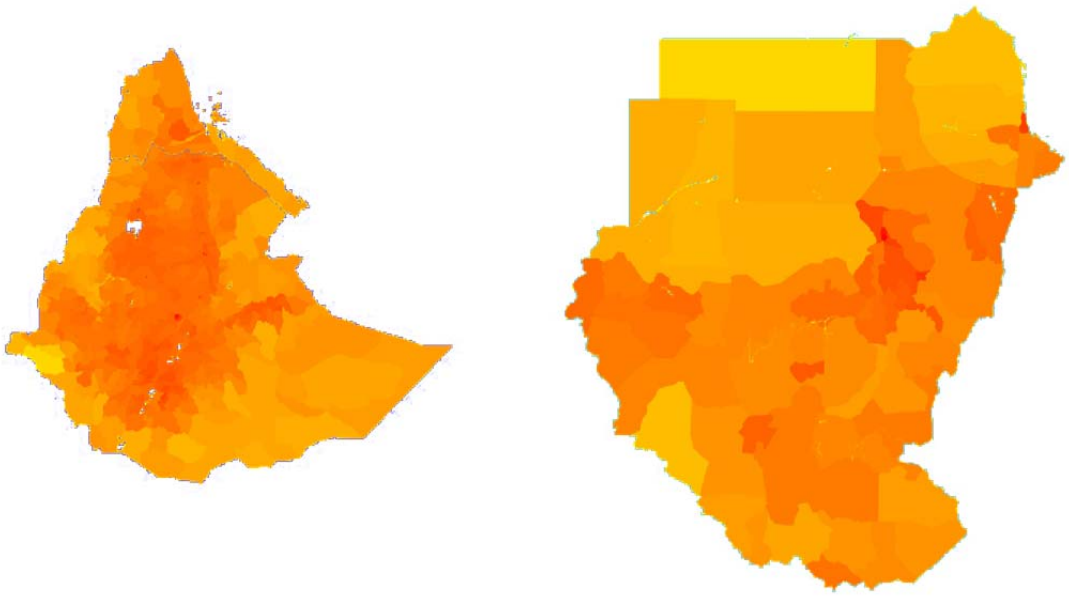
Ethiopia-Eritrea: Religion

Sudan: Ethnicity

Sudan: Religion

Each of colored polygons in each map describes the spatial spread of a population group with a specific trait.

Fig.2. Population distributions in Ethiopia-Eritrea (left) and the Sudan (right)



The yellow to red gradation displays different sizes of local population on each cell as measured by its logged population count.

Table 2. List of empirical data employed in the virtual states

Empirical Data	Data Sources	Corresponding Variable in a Virtual State
Spatial		
–Population Count	*Gridded Population of the World ver.3 (GPW3)* (CIESIN et al. 2004)	*Resources* of Each *PopCell* (multiplied by GNI per capita)
–Ethnicity	Constructed from the Existing Linguistic Distribution Maps (Asher and Moseley 1993); Lewis's Paper Map for Distribution of Somali Lineage Groups (Lewis 1998)	*Traits* of Each *PopCell*
–Religion	Derived from the Ethnicity Distribution; Also Consulting Other Sources (e.g., Ayabe 2000; Yaken 1999)	*Traits* of Each *PopCell*
–Region (Administrative Units)	Constructed from Supplementary Boundary Data of GPW3 for Ethiopia and the Sudan (CIESIN et al. 2004); Lewis's Paper Map for Somalia (Lewis 1998)	*Traits* of Each *PopCell*
Non-Spatial		
–GNI per capita	*African Development Indicators* (World Bank 2005)	*Resources* of Each *PopCell*
–Government Inclination	Derived from the Existing Case Studies (e.g., Gebru Tareke 1996; Johnson 2003; Lewis 2002; Markakis 1990; Widner 1992)	*Traits* of Government *Ruler*

Although CAVS is not constrained by any regional limitation, to date, the data have been taken exclusively from Northeast Africa (Eritrea, Ethiopia, Kenya, Somalia, and the Sudan), a region where violent processes of state integration and disintegration have continuously been observed over the past half-century. In other words, 'virtual Northeast African states' ('virtual Ethiopia,' 'virtual Sudan'…) built within a computer are the focus of investigation.

(2) Running virtual states

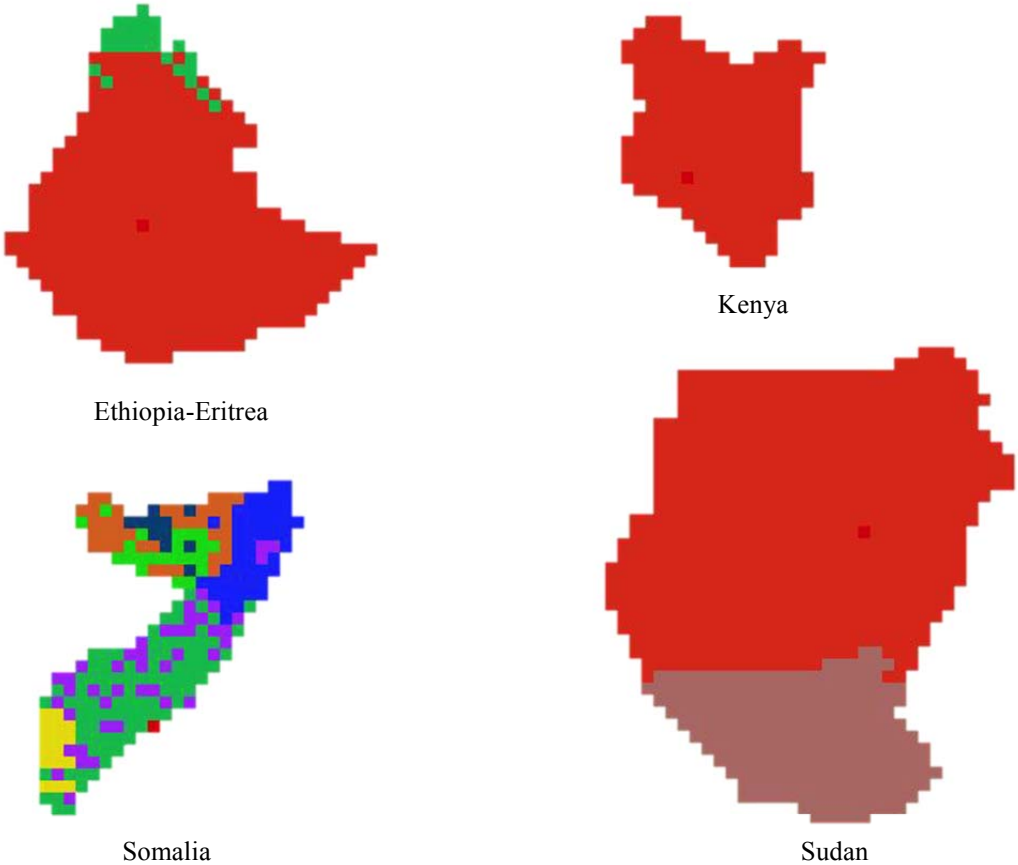
CAVS allows conflict researchers to pursue a variety of specific research endeavors. Particularly, as its platform is both spatially explicit and temporally dynamic, it has an obvious strength for handling the spatiotemporal aspects of civil conflicts, which have mostly remained theoretically intractable. Moreover, CAVS makes it possible to explore those aspects in the way that most of the preceding works have not: it simultaneously ensures intensive dialogues with, as well as extensive comparisons among, diverse empirical cases of conflict.

One direction that such fruitful exploration can take is reproducing and understanding actual conflicts. Can virtual states capture the diversity of conflict dynamics that has been observed in the corresponding states in reality? Starting from the initial condition of the exclusive rule by the government, the virtual Northeast African states indeed show diverse dynamics of conflict and territorial division as each *PopCell* continuously changes its affiliation with competing *Ruler*s in the way described above. The resulting spatial patterns of territorial division frequently converge to the ones that are largely consistent with the observed reality (see Fig. 3).[3] For instance, in a broad range of parameter values, virtual Sudan, once being put under the rule of a parochial government deeply inclined to Arab and Muslim

3. The general paucity of spatial data describing precise conditions of territorial order in each sovereign state has significantly hampered more vigorous, more quantitative evaluation of the model's explanatory power. Given that the availability of detailed spatial datasets on the location of conflict events has enabled researchers like Weidmann et al. (Forthcoming, 15-17) to employ sophisticated quantitative methods for empirical validation of their MAS models, the comparable development could bring huge benefits to CAVS.

inhabitants in the north, showed the same sort of tendency toward north-south civil war as the existing Sudan has historically shown. On the other hand, virtual Somalia suffered an extreme level of disintegration just like its counterpart in reality; while virtual Kenya, again mirroring actual Kenya, escaped such a serious fate over most of the time, maintaining its territorial unity over a long period of time. By mutually comparing these and other dynamics of conflict among different virtual states as well as by conducting controlled experiments in countless combinations of parameter values, one can gain a deeper understanding of conflict in the specific context of Northeast African countries.

Fig.3. Spatial patterns of conflicts in the virtual states



Each *PopCell* is colored on the basis of the *Ruler* to which it belongs. Specifically, the *PopCell*s colored red are those that remain under the rule of the *Initial Government*.

CAVS enables still another direction of exploration. Given a certain level of empirical validity of the model, one can fruitfully apply it to more practical and policy-oriented endeavors, especially prior or posterior investigation of specific policy interventions for managing conflicts. For instance, the author conducted hypothetical policy experiments in virtual Sudan, which investigated the effectiveness of several policy options in bringing peace to the country and its constituent parts (Sakamoto 2011b). One of the options examined is the partition of the country's territory along the north-south line, the option that was actually 'chosen' with the independence of South Sudan in July 2011. The investigation of this option in virtual Sudan suggested the ominous prospect of fierce conflicts among multiple contenders for the rule of the new country (see Fig. 4).

Fig.4. Spatial patterns of conflicts in Virtual North Sudan (left) and South Sudan (right)

Although these experiments are admittedly 'experimental' at this stage, the fact that they were conducted at all should not be underrated. Unlike most of the preceding theoretical models and empirical analyses, the CAVS platform can become a reliable 'laboratory' for pursuing a variety of focused and contextual policy investigation because of its close association with the empirical reality.

4. CAVS in Progress

Although the CAVS platform made a promising start, it is far from being an end product; it needs much more extension and sophistication for full-scale practical application. Accordingly, the GIS data and the MAS model are undergoing substantial improvement and extension. The following accounts describe the progress made so far. Many of the ideas for the updates came from the detailed comments and suggestions that the author received at the JICA Research Institute and elsewhere.

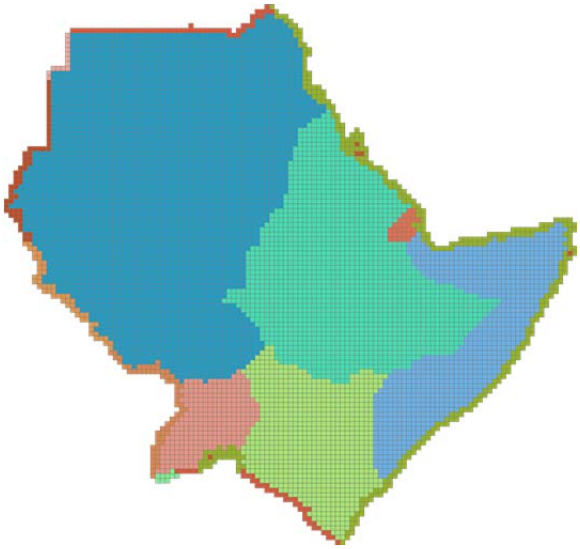
(1) Reconstructing the GIS dataset

The GIS database, which forms the basis for constructing the virtual states, was drastically restructured.

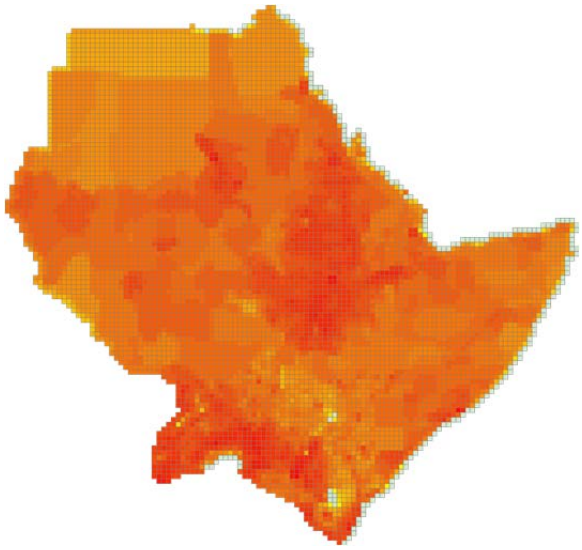
In the previous version, each of the GIS datasets employed such as demographic distribution and distribution of ethnic groups (see Table 2 above) was separately constructed as an independent raster dataset, and then exported to the simulation model as a separate input file. The overall data structure that resulted was somewhat complicated, making it cumbersome to manage or share the data. Such a condition has largely been streamlined. Specifically, all the datasets are now closely integrated under a common 'mesh-polygon' structure. In this upgraded structure, each data object corresponds to each tract of territory demarcated by a square mesh with a designated resolution (e.g., 15 * 15 square arc-minutes). Each object then has an arbitrary number of data fields such as population counts and ethnicity of inhabitants. In other words, the new structure allows for including unlimited combinations of GIS datasets in its data fields, so long as each of them consists of mesh-shaped polygon objects, or is convertible to such a dataset (see Fig. 5).[4]

4. For instance, the spatial datasets on traits distributions, which were originally built in an ordinary vector data format with arbitrary shapes of polygons (see Sakamoto 2011a, 79-86), were converted to mesh-polygon data. They also underwent additional measures of data processing such as interpolation and resampling.

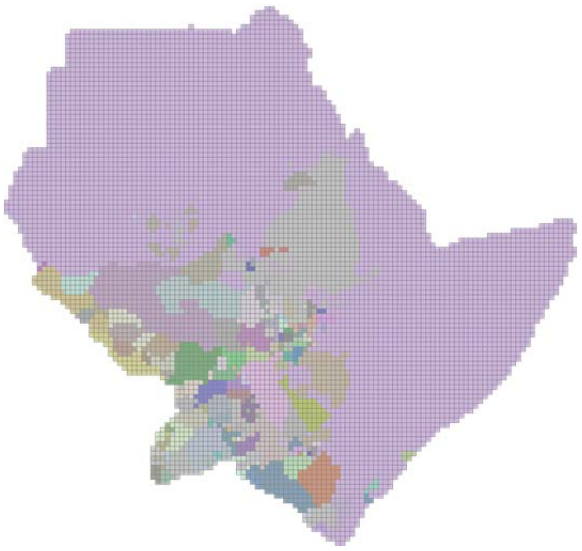
Fig.5. Mesh-Polygon spatial data on Northeast African countries



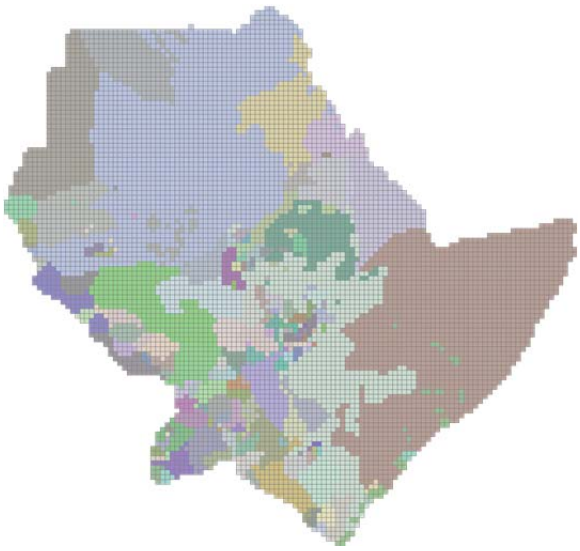
State Configuration in 1990



Demography in 1990



Ethnicity



Religion

Moreover, as easily seen from Fig. 5, in the updated version of the GIS database, the data management is no longer country-based as in the previous one. At least logically, the constituent datasets have become free from any geographical constraint, including the state

boundaries and territories.[5] The boundaries and territories, on their parts, are now included in the database, constituting its data fields as independent variables. Accordingly, the whole database is spatially extensible to any geographical range. The implications of this major change for CAVS as a whole will be explored below.

As a result of these changes, which on the whole significantly unify a vast array of spatial data, data management has become much easier as well as more flexible. At the same time, data portability has also been substantially increased. For example, it is now possible to export the whole database in the Shapefile format, a standard vector data format.

(2) Strengthening the interface between GIS and MAS

Specifications for the import of GIS data into the MAS model have become much more flexible than in the previous version.

In CAVS, the GIS data and the MAS model are the two major component parts, and they are independent from each other, at least conceptually. In practice, however, the data and the model were inseparable in the preceding platform. This means that the composition of each virtual state strongly depended on a particular set of empirical data that was originally employed, making it difficult to swiftly reflect any update or replacement made in the empirical data on the relevant aspects of the virtual states concerned.

The updated platform has largely overcome this potentially serious limitation. The key is the introduction of a new interface through which one can flexibly specify relationships between data fields of each mesh object in the GIS database and variables of the corresponding *PopCell* agent in the MAS model. If the database includes several sets of data on population distribution from different periods of time, for example, the interface allows for prompt selection of any one of them, which is then utilized for the formation of virtual states. Moreover,

5. There are several practical constraints, however. The most obvious one is the potentially huge computational load that geographically extensive GIS data have on a computer. Accordingly, the current GIS database for CAVS exclusively consists of the data on eight countries in Northeast Africa, namely, Djibouti, Eritrea, Ethiopia, Kenya, Somalia, South Sudan, the Sudan, and Uganda.

it also enables one to specify some of the variables in the model in a more detailed manner. For instance, it is no longer necessary to depend exclusively on the simple combination of population counts and country-level GNI per capita for forming the resource distribution of each virtual state. Instead, it has become possible to construct a virtual state with a more realistic makeup by employing other sources of information such as spatial distributions of household income and natural resources.

As a result of these updates, one can construct several 'versions' of a virtual state from various alternative data sources, which greatly enhances the model's capacity to capture diverse aspects of the complex reality. This is also valuable because it promotes the verification of each virtual state's behavior and its sensitivity to changes in different variables and parameters in the model.

(3) Extending the MAS model

The MAS model itself was greatly strengthened. The most conspicuous changes can be found in its extended coverage of international and transnational factors.

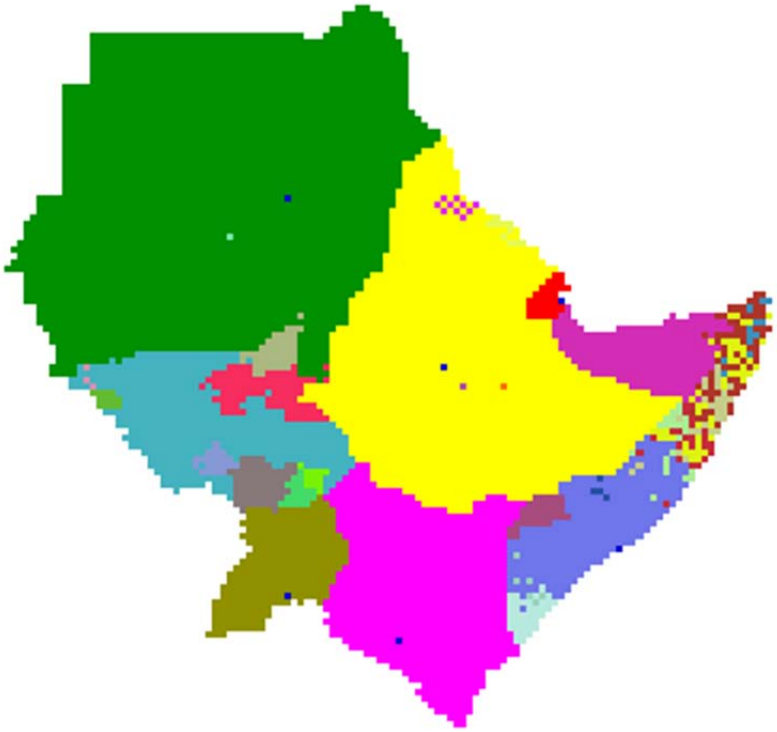
One of the problems that have frequently been pointed out about the previous version of the model is its inability to explicitly deal with things happening beyond the state border.[6] A virtual state was mostly closed and self-contained as a system of interacting agents. Such an aspect sometimes seriously constrains the model's applicability to actual cases of conflict. The changes made to the model mostly deal with this obvious problem.

One way of tackling the problem is to extensively restructure the model so that one can form an arbitrary number and combinations of states over the same virtual space, and implement simulations in these states simultaneously (see Fig. 6). This substantial extension has already been partially introduced, although at present each of the virtual states thus created,

6. The model, however, can indirectly incorporate external factors through some of the variables such as a *Ruler*'s *External Resources*, which specifies the amount of the exogenously generated resources accruing to the *Ruler* concerned. See Sakamoto (2011a, 192-198) for further detail.

without any interaction with the surrounding states, simply behaves as it did in the previous version. Modeling the relationships among mutually adjoining states and their impact on conflict dynamics within each state, which have been a much discussed topic in the conflict studies (e.g., Brown 1996), is one of the immediate tasks lying ahead.

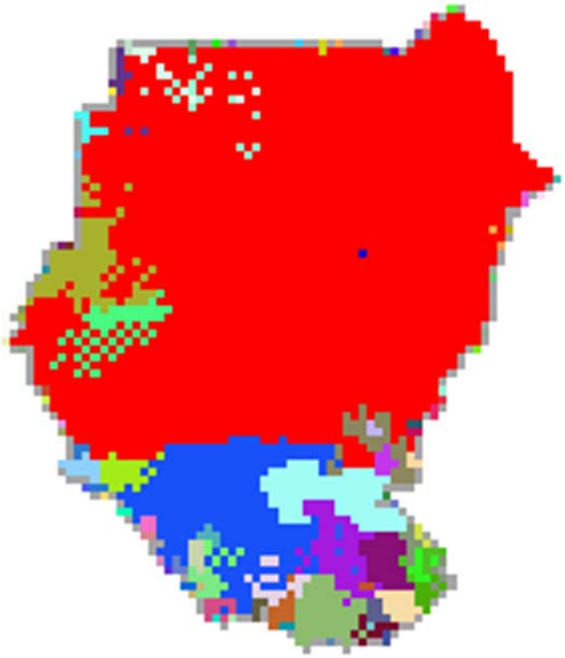
Fig.6. Simultaneous simulations in multiple virtual states



This image captures various dynamics of territorial integration and disintegration that six virtual Northeast African states are generating in parallel. As in Fig.3 and 4, the difference in colors indicates the difference in *Ruler*s with which *PopCell*s are affiliated. Note that, at the current stage, the model does not include any rule specifying cross-border interactions among mutually adjoining states. Accordingly, what is shown in the image remains a mere collection of six separate dynamics, implemented independently of each other.

Moreover, the upgraded model allows for a more controlled form of incorporation of external factors: one can specify a fixed 'boundary condition' in order to control trans-boundary influences exerted on a given virtual state. Instead of mutually linking the endogenous dynamics of multiple virtual states, this extension basically focuses on one country, and exogenously generates a spatial configuration of *Ruler* agents surrounding the territory of the country in question (see Fig. 7). Each of the boundary *Ruler*s has a fixed 'sanctuary' beyond the state border, and its location as well as the *Ruler*'s traits can be explicitly designated or randomly generated. The extension captures the often-observed trans-boundary infiltration of insurgents, which have some support and a base in the adjacent country.

Fig.7. Simulation in virtual Sudan with a randomly generated boundary condition



In this panel, the territory of virtual Sudan is surrounded with an additional string of gray PopCells (except for the coastal area in northeast). Some of these cells, which are colored differently, host randomly generated 'boundary Rulers.' The latter agents are exerting trans-boundary influence on the PopCells located within virtual Sudan.

Apart from dealing with international and transnational factors, there are other updates made to the model as well. One of them is the introduction of several options for designating a spatial resolution of a mesh structure imposed on the territory. In the preceding platform, there was in effect no option in this regard: the territory of each virtual state was gridded at a fixed resolution of 30 arc-minutes (approximately 55km at the equator) both in latitude and in longitude. In the updated version, in contrast, 5, 10, 15, 30, and 60 arc-minutes can be selected. Higher resolution ensures more detailed and finer composition of a virtual state, while it also implies heavier computational load of simulations because *PopCell* agents multiply accordingly.

5. Projects Underway

These and other changes in the CAVS platform considerably broadened the range of its application, making it possible to implement a variety of interesting investigations with clear policy implications. What follows are some of the investigations currently underway. While still being at a nascent stage, these projects, with proper feedback, could further enrich the CAVS platform, making it a much more powerful tool for conflict analyses.

(1) Trans-boundary influences

Many civil conflicts are not 'domestic' in the strict sense of the term because of the existence of a variety of influences and pressures coming from outside the state boundaries. Most of the historical conflicts in Northeast Africa, for example, are exactly of this nature. But how do such trans-boundary factors work, and how crucial are they? By employing the extended MAS model, which allows for controlling boundary conditions of virtual states in different ways, these questions can now be directly addressed in the context of Northeast African countries.

A case in point is the appalling Darfur conflict in western Sudan. In the previous version of the platform, this case constituted one of several noticeable divergences between the virtual and actual worlds: the conflict in Darfur largely remained latent in virtual Sudan (Sakamoto 2011a, 132). Things can change drastically with the introduction of a certain form and amount of trans-boundary influence, given the almost inseparable existence of such influence in the actual Darfur conflict. Investigation of the dependence of conflict dynamics on different boundary conditions in this and other cases can bring about important insights about transnational dimensions of civil conflicts as well as outside interventions in these conflicts.

(2) More realistic spatial composition

Each virtual state has its own distribution of human and material resources. In the original CAVS platform, this distribution was formed somewhat crudely from the population distribution of the country concerned and its aggregate GNI data at the national level. As was mentioned in the previous section, the more flexible interface between empirical data and the model in the upgraded platform makes it possible to construct more elaborate resource distributions.

Currently, such endeavor is underway for some countries in Northeast Africa where detailed socio-economic data such as household surveys and information on natural resources are available. For example, newly independent South Sudan is such a country, providing detailed survey data at the sub-national level online.[7] In combination with GIS data on sub-national administrative units within the country, one can obtain fairly detailed spatial data on the country's resource distribution. This data then enables various policy-oriented examinations, including an assessment of the possible influence of regional variation in development on the occurrence of conflict in each locality. Another important subject of

7. Visit the website of the country's National Bureau of Statistics (http://ssnbs.org/. Accessed on January 23, 2013).

inquiry is the persisting confrontation over oil between the two Sudans, which has now made all the oil fields in the South effectively inoperable,[8] and its impact on the unity and survival of the new country.

(3) Aid flow and its effectiveness

In CAVS, one can investigate the effectiveness of outside aid in preventing or containing conflict in a given country through control of the amount of external resources accruing to the government in the corresponding virtual state. In the extended model, it becomes possible to specify the spatial allocation of aid in a detailed manner by using GIS data on sub-national geographical or administrative units (see Fig. 8). For example, the same amount of aid resources can be deployed evenly over the state territory, or can be concentrated on particular sub-national regions. Investigation of these alternative ways of involvement and their possible consequences in terms of conflict prevention and containment has obvious policy relevance, especially for the purpose of efficient use of outside aid. Again focusing on South Sudan, such policy experiments will be extensively conducted in the virtual state that approximates that country.

Fig.8. Administrative units (states) in South Sudan

8. At the end of September 2012, the two sides reached an agreement on restarting oil exports through Port Sudan. However, a substantial amount of uncertainty remains as to its implementation.

Lastly, even these extensive endeavors might be only a tiny portion of what CAVS can possibly achieve. With due consideration of tractability and feasibility, one can explore and expand the field of its application still further, which in turn requires a varying degree of extension and refinement of the platform. The following are somewhat speculative examples of the possible development of CAVS.

–Further specification of composition of virtual states: examples include explicit treatment of different sorts of human connectivity through various communication and transportation networks; and sectoral disaggregation of *PopCells*' resources (e.g., agriculture, industry and service sectors) in order to conduct detailed assessment on the effects of various development policies.

–Detailed specification of governing apparatus: the priority in this regard is incorporating particular institutional aspects of statehood into the relevant virtual states. In the case of African states, these include often-referred characteristics of personal rule and distributional style of politics (e.g., Reno 1998; van de Walle 2001).

–Broader treatment of international factors: dynamics of civil conflicts are often crucially influenced by factors far beyond state boundaries. A variety of connections that each state has with the wider international society can be fruitfully incorporated into the platform. Examples are extensive: from modeling diverse channels of external links that each state can have (Peiffer and Englebert 2012) to examining more structural and longer-term impacts coming from distribution of power in the international system (Kalyvas and Balcells 2010).

6. Conclusion

The CAVS platform is not only a novel but also a quite powerful tool for analyzing civil conflicts. It is firmly grounded on empirical data; it captures the observed dynamics of conflicts; and it is flexible enough to incorporate diverse relevant factors and to embrace different research objectives. All in all, the platform opens up the possibility for deeply integrated theoretical, empirical and policy analyses, which enable researchers to answer a wide range of hitherto formidable research questions and to devise various policy prescriptions in a highly contextual manner.

In particular, CAVS offers a pioneering example of experimental approaches to policy research. In situations as threatening as civil conflicts, controlled policy experiments involving actual human subjects are simply impossible. Simulation in a 'realistically virtual' environment like virtual states in CAVS can be a pragmatic and promising alternative for prior or posterior assessment of policy interventions in these situations. Moreover, because of its highly integrated character described above, the distinction between 'academic' and 'policy/practical' is largely irrelevant to CAVS: one can proceed almost seamlessly, and often even unconsciously, from one to the other, and vice versa. This means that the CAVS platform provides a natural meeting point between academic researchers and policy practitioners, whose contribution and exchange of diverse expertise and interests would further enrich the platform. Indeed, increasing the interaction between the two still-divided camps for common endeavors might be a quite stimulating experiment in itself.

References

Asher, Ron. E., and Christopher Moseley, eds. 1993. *Atlas of the world's languages*. Oxford: Routledge.

Ayabe, Tsuneo, ed. 2000. *Sekai minzoku jiten* [Encyclopedia of the world's ethnic groups]. Tokyo: Koubundo Publishing.

Brown, Michael E., ed. 1996. *The international dimensions of internal conflict*. Cambridge, MA: MIT Press.

Bhavnani, Ravi, and Hyun Jin Choi. 2012. Modeling civil violence in Afghanistan: Ethnic geography, control, and collaboration. *Complexity* 17 (6): 42-51.

Cederman, Lars-Erik. 1997. *Emergent actors in world politics: How states and nations develop and dissolve*. Princeton, NJ: Princeton University Press.

———. 2008. Articulating the geo-cultural logic of nationalist insurgency. In *Order, conflict and violence*, ed. Stathis N. Kalyvas, Ian Shapiro, and Tarek Masoud. Cambridge: Cambridge University Press.

Cederman, Lars-Erik, and Luc Girardin. 2006. A roadmap to realistic computational models of civil wars. Paper presented at the 1st World Congress on Social Simulation, Kyoto, August 21–25.

Center for International Earth Science Information Network (CIESIN), Columbia University, and Centro Internacional de Agricultura Tropical (CIAT). 2004. *Gridded Population of the World (GPW), ver. 3*. Palisades, Washington, DC.: CIESIN, Columbia University. http://sedac.ciesin.org/gpw/ (accessed October 1, 2012).

Collier, Paul, and Anke Hoeffler. 2004. Greed and grievance in civil war. *Oxford Economic Papers* 56 (4): 563-95.

Cunningham, Kathleen Gallagher, and Nils B. Weidmann. 2010. Shared space: Ethnic groups, state accommodation, and localized conflict. *International Studies Quarterly* 54 (4): 1035-54.

Fearon, James D. 1998. Commitment problems and the spread of ethnic conflict. In *The international spread of ethnic conflict: Fear, diffusion, and escalation*, ed. David A. Lake and Donald Rothchild. Princeton, NJ: Princeton University Press.

———. 2004. Why do some civil wars last so much longer than others? *Journal of Peace Research* 41 (3): 275-301.

Fearon, James D., and David D. Laitin. 2003. Ethnicity, insurgency, and civil war. *American Political Science Review* 97 (1): 75-90.

Gebru Tareke. 1996. *Ethiopia: Power and protest*. Asmara: Red Sea Press.

Hegre, Håvard, Ranveig Gissinger, and Nils Peter Gleditsch. 2003. Globalization and internal conflict. In *Globalization and armed conflict*, ed. Gerald Schneider, Katherine Barbieri, and Nils Peter Gleditsch. Oxford: Rowman & Littlefield.

Johnson, Douglas H. 2003. *The root causes of Sudan's civil wars*. Oxford: James Currey.

Kalyvas, Stathis N., and Laia Balcells. 2010. International system and technologies of rebellion: How the end of the cold war shaped internal conflict. *American Political Science Review* 104 (3): 415-29.

Lewis, Ioan M. 1998. *Peoples of the Horn of Africa: Somali, Afar and Saho*. Asmara: Red Sea Press.

———. 2002. *A modern history of the Somali: Nation and state in the Horn of Africa*. 4th ed. Oxford: James Currey.

Lim, May, Richard Metzler, and Yaneer Bar-Yam. 2007. Global pattern formation and ethnic/cultural violence. *Science* 317: 1540-44.

Lustick, Ian S., and Dan Miodownik. 2009. Abstractions, ensembles, and virtualizations: Simplicity and complexity in agent-based modeling. *Comparative Politics* 41 (2): 223-44.

Markakis, John. 1990. *National and class conflict in the Horn of Africa*. London: Zed Books.

Østby, Gudrun, Ragnhild Nordås, and Jan Kentil Rød. 2009. Regional inequalities and civil conflict in Sub-Saharan Africa. *International Studies Quarterly* 53 (2): 301-24.

Peiffer, Caryn, and Pierre Englebert. 2012. Extraversion, vulnerability to donors, and political liberalization in Africa. *African Affairs* 111 (444): 355-78.
Posen, Barry R. 1993. The security dilemma and ethnic conflict. In *Ethnic conflict and international security*, ed. Michael E. Brown. Princeton, NJ: Princeton University Press.
Reno, William. 1998. *Warlord politics and African states*. Boulder: Lynne Rienner Publishers.
Sakamoto, Takuto. 2011a. *Ryouiki touchi no tougou to bunretsu: Hokutou Afurica shokoku wo jirei to suru maluchi-ēgento simyulēshon bunseki* [Integration and disintegration of territorial rule: Multi-agent simulation analysis with application to the northeast African countries]. Tokyo: Shosekikobo Hayama Publishing.
———. 2011b. Jizokuteki heiwa no tameno maluchi-ēgento simyulēshon: Minami Sudan dokuritsu wo maenisite [Multi-agent simulation for sustainable peace: Facing the coming independence of South Sudan]. A Study on the dynamism of the international political order with application of the multi-agent models, Working Paper Series 11: 1-19.
———. 2013. Exploring spatial dynamics of civil conflicts in virtual Africa: A new research design. Unpublished manuscript. University of Tokyo.
Snyder, Jack, and Robert Jervis. 1999. Civil war and the security dilemma. In *Civil wars, insecurity, and intervention*, ed. Barbara F. Walter and Jack Snyder. New York, NY: Columbia University Press.
van de Walle, Nicolas. 2001. *African economies and the politics of permanent crisis, 1979-1999*. Cambridge: Cambridge University Press.
Walter, Barbara F. 1997. The Critical Barrier to Civil War Settlement. *International Organization* 51 (3): 335-64.
———. 1999. Designing transitions from civil war. In *Civil wars, insecurity, and intervention*, ed. Barbara F. Walter and Jack Snyder. New York, NY: Columbia University Press.
Weidmann, Nils B. 2006. Settlement patterns and the success of insurgencies: The territorial control model. Paper presented at the 1st World Congress on Social Simulation, Kyoto, August 21–25.
Weidmann, Nils B., Håvard Hegre, and Clionadh Raleigh. 2006. Modeling spatial and temporal patterns of civil war. Paper presented at the 102nd Annual Meeting of the American Political Science Association, Philadelphia, August 31–September 3.
Weidmann, Nils B., Jan Ketil Rød, and Lars-Erik Cederman. 2010. Representing ethnic groups in space: A new dataset. *Journal of Peace Research* 47 (4): 491-99.
Weidmann, Nils B., and Idean Salehyan. Forthcoming. Violence and ethnic segregation: A computational model applied to Baghdad. *International Studies Quarterly*.
Widner, Jennifer A. 1992. *The rise of a party-state in Kenya: From Harambee! to Nyayo!* Berkeley, CA: University of California Press.
World Bank. 2005. *World Bank Africa database 2005 (CD-ROM)*. Washington, DC: World Bank Publications.
Yaken, Mohamad Z. 1999. *Almanac of African peoples and nations*. London: Transaction Publishers.
Yamakage, Susumu. 2009. *Modeling and expanding artificial societies*. Tokyo: Shosekikobo Hayama Publishing.

Abstract (in Japanese)

要約

本稿では、マルチエージェント・シミュレーション（MAS）および地理情報システム（GIS）に依拠した、国内紛争分析のための新たな研究手法を、その最新の展開に焦点をあてて紹介する。「仮想国家紛争分析（Conflict Analysis in Virtual States, 以下 CAVS)」と名付けられたこの手法は、GIS データなど経験データに基づいて仮想的に構成した主権国家の領域上で、国内武力紛争の空間的な動態を、国家の領域的な統合・分裂の過程とともにシミュレートするものである。実在する国家を近似した環境において、制御されたさまざまな仮想実験を行うことで、紛争に対する理解を深めることができるほか、政策介入の効果の事前・事後検証のためのプラットフォームとして活用されることも期待される。このような目的に資するため、CAVS では、GIS データから MAS モデルにいたるまで、現在さまざまな拡張を行っている。本稿では、こうした拡張（たとえば､仮想国家に対する国外からの影響・介入の明示的な取り扱いなど）を、関連する新たな研究プロジェクトとともに概観していく。