Invasion, Self-Defense and Third-Party Enforcement: Modeling Emergent Property Rights with Applications to Economic History[*]

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Abstract: I develop an agent-based model to explore the emergence of conventions establishing property rights over various resources. I show how the structure of property rights varies with the distribution of resources, renewability, and relative scarcity.

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I. Introduction

The California Gold Rush of 1848/49 sent thousands of miners and prospectors in search of gold to the unincorporated hills of California where they squatted on Federal land and coexisted in relative peace despite the absence of legal authority. Complex property rights developed to coordinate productive activities and reduce the frequency and scope of conflict. Miners made claims to land, cooperated to respect those claims, and developed various rules of transfer to cope with their circumstances. These rules were often compiled into miners' codes, and although they had no original legal standing, eventually many of the codes were incorporated into the property and mining law of the newly formed State of California when the legislature passed statutes that instructed judges to cite the mining codes as precedent (Umbeck 1977).[1]

From the remaining historical documents, much can be learned about the structure and form of the property rights that developed during the Gold Rush, but the process by which those particular rights were created and adopted in the absence of government support was not so neatly preserved. In general, this is true of the history of property rights. A number of competing and complementary theories have been articulated to explain the initial formation of property rights *in general*, but few theories explain why property rights have usually varied greatly with time, location, and the economic environment. For example, Demsetz argues that property rights (exclusion) will "develop to internalize externalities when the gains of internalization become larger than the cost." (1967, p. 350) In the case of the Gold Rush, this implies the existence of some critical mass of miners or critical price of gold, that when reached will lead to the spontaneous creation of fully functioning property rights.[2] However, as Umbeck notes, this account overlooks the costs of negotiating the structure of those rights as well as the costs of enforcement.[3] His own account, formalizing the intuition of Cheung (1970) that (all else equal)

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[1] Casari (2007) describes a similar process in which informal institutions to protect property rights in the Italian Alps were eventually converted into private-order charters with the force of law. Dower (2008) suggests that such a process will be common because property rights that exploit local knowledge will be easier to define and enforce.

[2] Since the theory specifies neither a mechanism, political process, nor the content of the rights, Eggertsson (1990) refers to Demsetz's account as the "naïve theory" of property. The naïve theory is likely to be predictive only when multiple legally enforceable property rights arrangements already exist. For example, Gerard (2001) shows that after the General Mining Law of 1872 established patented (full title) and unpatented claims, contract choice changed with the frequency of claim disputes. When disputes diminished, miners decreased demand for claim patents. See also, Libecap's (1978) theory of legal change in mineral rights.

[3] Krier (2009) cites later comments by Demsetz suggesting that he never intended to develop a theory of *how* property evolves; rather he was interested only in *why*.

contractually established property rights will become increasingly exclusive as the value of the resource rises, acknowledges these issues and defines cost conditions under which contracts for the protection of property will develop.

While Umbeck adds to the narrative provided by Demsetz, his account is also inadequate because the *content* of the property rights remains unspecified. Property rights can take any number of forms, and as I will discuss, the rights that developed to allocate mining land in the California Gold Rush do not match the standard image of secure and inviolable property. Briefly, there were a number of circumstances in which miners would move onto already-claimed land and work the claim as their own; that is, miners would steal the claims of other miners. However, these unilateral takings (so-called "claim jumps") received the social sanction of other miners and were codified in the mining codes, creating a system of relatively insecure property rights to mining claims. Why did property rights in this time and place take this particular form, and why do they differ elsewhere?

Clay and Wright (2005) argue that the structure of property rights in the Gold Rush emerged as a response to the distribution of gold in the environment. Specifically, because gold deposits are distributed unevenly, that is, with a few high-yield areas and a great many very low-yield areas, the Gold Rush can be viewed as a race to find the high-yield deposits, in which miners moved from area to area, claiming plots of land rapidly, hoping to strike rich. Thus, it was in the interest of miners to permit others to jump claims because they wanted to reserve similar rights for themselves. Hence, in the California Gold Rush, consideration was given to both original claimants and claim jumpers, and little effort was expended in third-party enforcement.

However, distribution is not the only resource characteristic with the potential to alter the structure of property rights. For example, Baker (2003) models repeated games of conflict among hunter-gatherers and suggests that the more plentiful and predictable the resources, the more secure will be the rights to land containing those resources. Outside of economics, such claims are well documented empirically. Maher and Lott (2000) survey the literature on territoriality in non-human species to explore the effects of resource distribution, abundance, predictability, and storability. They find that extreme values (low or high) along any of these scales leads to relatively low territoriality, while moderate values lead to increased territoriality.

Taken together, these theories suggest that the structure of property rights will be sensitive to resource characteristics in a number of dimensions. To test the effects of changes in resources on property rights, I develop a general agent-based model of search, resource extraction, and property rights formation. Specifically, I analyze the effects of distribution, renewability, and scarcity. Agents are instantiated with binary norms for invasion, willingness to engage in self-defense, and third-party enforcement. These norms guide agents' behavior as they move on a grid – similar to that in Axtell and Epstein (1996) – in search of a resource. Invading agents may move onto other agents' claims, and these attempted invasions may lead to costly disputes that are settled by majority rule among local agents. Norms adjust over time via virtual natural selection, and I explore the hypotheses and suggested counterfactuals of Clay and Wright (2005), Baker (2003), and Maher and Lott (2000), among others, by comparing the success of various agent types over time as measured by their prevalence in the population under various resource characteristics.

The following claims find support in the data: 1) All else equal, low variance resources lead to more secure rights in property than high variance resources; 2) Scarcity is associated with a large decrease in the security of property rights, particularly when resource yields are high variance; 3) decentralized third-party enforcement is rare in all cases. Not only are property rights structures sensitive to the characteristics of resources; they are sensitive in predictable and consistent ways. Section II reviews previous literature on the development of property rights, illustrating examples with the well-documented case of the California Gold Rush. Section III describes the model. Section IV details the results of regression analysis and an overlapping generations version of the model, and Section V concludes.

II. Property Rights

Before exploring how the development of property rights arrangements is determined by the characteristics of resources, it is important to understand the historical debate over the source of property rights. Since the model explores the development of property rights in an anarchic world, I first establish that property rights are possible without state enforcement. Then I show how models of emergent property rights have evolved to explain the case of the California Gold Rush. This example and additional empirical and theoretical literature motivate the design of the model and my hypotheses.

II.A. The Origins of Property

Those engaged in the debate about the origin and development of property rights have coalesced into two main groups whose major dispute is over the role of the state in property formation. There are those who, following Hobbes (1651), argue that property rights must be imposed and enforced from the outside by some legal authority if they are to take root. As Furubotn and Pejovich (1972, p. 1140) put the claim: "a theory of property rights cannot be truly complete without a theory of the state."[4] The focus of the research program operating under this theory of property has largely been to explain the impact of various property rules – "to show that the content of property rights affects the allocation and use of resources *in specific and predictable ways*." (*Ibid*., p. 1139, emphasis in the original) Thus, many economists may favor the Hobbesian view because it complements their attempts to analyze the effects of *exogenous* changes in rights on the allocation of resources.[5]

However, one shortcoming of this view is that it equates property rights with the existence of state-controlled institutional structures for the punishment of appropriators. This muddled perspective ignores that recourse to punishment mechanisms (public or private) necessarily implies the violation of a pre-existing right. States may *support and enhance* property rights by punishing violators, and it is true that once states are established, they are able to define and codify the set of violations. But the existence of property rights need not have its origin in state power. In fact, the emergence of the state occurred relatively late in human history, and evidence of distal exchange networks – implying the existence of property rights to the goods being exchanged – far predates evidence of large-scale state-like social organization. (Cunliffe 2008) Thus there are others, following Pufendorf (1672) and Hume (1740) who argue that property rights emerge as conventions out of repeated interactions, with the goal of ordering social interaction and mitigating conflict. Property is established by consent (tacit or explicit) to respect possession and "humanity [or the members of a specific social group] might be viewed as consenting to those individual claims to which no one objects." (Rose 1985, p. 74) Much research in economics – both theoretical and empirical – has been performed in the last 40 years

[4] See also Bentham (1802), Westermarck (1908), Sened (1997), and Wyman (2005).

[5] Cheung (1968) offers one exception to this trend in his examination of the effects of sharecropping contracts. He shows that as long as ownership is private, sharecropping agreements are welfare neutral, but he admits that the origin of such contracts remains a mystery and suggests that one might ask why various contracts are relatively prevalent in one locality and not others.

to understand how property rights can be created in the absence of the state, and this project continues in that tradition.

Theoretical treatments that conceive of property rights formation as the elimination of costly conflict have generally assumed a Hobbesian "state of nature" and described conditions under which cooperation (the absence of resource allocation toward conflict) will be possible. For a reasonably broad set of games, economists have been able to show that conflict over a resource can be avoided in some equilibria with myopically self-interested players. For example, Skaperdas (1992) describes a state of nature in which cooperation may emerge if conflict is expected to be unproductive. Grossman and Kim (1995) model investment decisions in offensive (appropriative), defensive, and productive activities and show conditions under which no resources are invested in offense. Hafer (2006) shows that in a game of repeated conflict over a resource, possession signals success in prior conflicts and can establish expectations among potential contestants that support private property.[6] Additional theoretical research by Maynard Smith and Parker (1976), Sugden (1989) and Young (1993, 1998) explores the evolution and stability of conventions (coordination on a single equilibrium when many exist), including a convention in which first possession or some other focal point (correlated or uncorrelated asymmetry) is the source of property.

Furthermore, empirical studies have repeatedly demonstrated the existence and effectiveness of non-state governance structures that are able to reduce conflict over resources and eliminate potential sources of inefficiency that are generally assumed to follow from the absence of secure external protection of property. The classic treatment in Ostrom (1990) describes numerous non-state mechanisms developed to solve common property (open-access) problems in irrigation, grazing, and so on. Ellickson (1991) depicts informal, private dispute settlement mechanisms among cattle ranchers in Shasta County, CA that operate effectively

[6] Muthoo (2004) describes conditions under which a two-person repeated game of production and conflict can support equilibria without conflict (with property rights) and shows that permitting transfers of output can expand the set of parameters that support property rights. Gintis (2007) gives a behavioral explanation of "natural" property rights. He argues that the endowment effect (loss aversion) implies that first possessors will be willing to expend more effort to defend their possession than potential contestants in a war of attrition, creating an equilibrium in which contestants do not to attempt to seize and possessors fend off any such attempt. Similarly, Stake (2004) argues for the existence of 'property instinct'. Boyce and Bruner (2009) show conditions under which private property protection may be funded by voluntary contributions as a public good.

alongside unused state mechanisms.[7] Laboratory experiments by Kimbrough, Smith and Wilson (2010) describe how human subjects construct property conventions to support specialization and exchange when theft is costless.[8] Yet, the great part of this work has gone to show the *possibility* or *existence* of non-state mechanisms for the protection of property. Very little has been done to explore why property rights take on one set of specific characteristics in a given context and not in another. In this respect, the case of the California Gold Rush of 1849 is one of few exceptions.

II.B. Property Rights and Resource Characteristics: Theory and Empirics

As a case study of the impact of resource characteristics on the development of property rights, the California Gold Rush is exceptional because the history is well documented and the economic environment is simple and clear. Gold in California was sparsely distributed on the landscape. There were a few high-yield claims and a great many very low or zero-yield claims. Furthermore, because gold was distributed unevenly, there was strong incentive to search widely *and quickly* for gold in hopes of finding a high-yield claim. If strong, perfectly protected private rights to mining claims had immediately become the norm in such an environment, the miner or prospector that traveled fastest would have been likeliest to succeed. By claiming a large number of plots quickly, an individual miner could increase his probability of finding a high-yield claim. However, during the Gold Rush, California had not yet been granted statehood and there was no authority available to protect private claims to land. Nor was there a functioning market in land to allow a buyer to purchase a large number of claims quickly, as no individual technically owned the land he worked. In fact, the first gold miners were squatters on Federal land, so for property rights in mining claims to take root required the consent and cooperation of other local miners, that is, claim rights had to take the form of a convention. (McDowell 2002, 2004)

Given the desirability of rapid search and the absence of external legal protections, any attempt to stake a large number of claims would run into enforcement problems. Other miners,

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[7] Additionally, Dennen (1976) shows how private cattlemen's associations in the American west protected members' stock by limiting entry onto common grazing lands. Clay (1997) details private-order mechanisms that facilitated long-distance trade between merchants in Mexican California absent state enforcement of contracts.

[8] Kimbrough (2010) employs agent-based models and human subject experiments to explore how conventions to respect property develop by turning theft into exchange. Jaworski and Wilson (2009) show how the development of property conventions in the lab is facilitated by endogenous group formation via migration. Powell and Wilson (2008) investigate Hobbesian environments in the lab and find that some subjects are able to overcome the temptation to plunder.

facing the same incentives to search would be inclined to appropriate those claims that could not be actively defended.[9] While miners faced strong incentives to invest in defense with hopes of maintaining a large portfolio of claims, such effort is costly (in loss of life, energy, time, etc.) and miners' resources were limited. Umbeck (1981) argues that property rights were initially allocated proportionally to the fighting ability and resources of claimants and to the productivity of the land. In other words, for miners with equal fighting abilities, the allocation resulting from conflict should equalize the marginal product of a day's work, and knowing this, miners should contract to provide each with the amount of land that he could acquire by conflict (supposing that the resource is valuable enough to make costly negotiation worthwhile). If the gold were evenly distributed, then claims would be of equal size, and if gold were unevenly distributed, higher-yield areas should produce smaller claims.

In a static environment where all relevant parties know the productivity of the land *ex ante*, contracts of this form could be negotiated. However, miners had incomplete information about the yields of various plots of land, and the incentive to search (and hence to appropriate the claims of other miners) remained strong. Because of the uncertain and uneven distribution of gold, the stability of claims implied by contractual allocation was undesirable. After reviewing the historical evidence contained in the extant mining codes of the era, Clay and Wright (2005) suggest that property rights in the Gold Rush were actually quite *insecure* and gave relatively equal standing to both claim holders and claim jumpers. The codes list detailed conditions under which the rights to a claim belong to either a claim jumper or the original claimant.[10] Miners were allowed private rights to claims that they worked with sufficient frequency, but miners could not expect to retain rights to claims that they were unable to work.

Here an economist in the tradition of Hobbes might suppose that the fluidity of property rights suggests some deficiency resulting from the absence of state enforcement, but Clay and Wright (2005) argue otherwise. They contend that informal property rights conventions ought to respond appropriately to the incentives presented by the resource and environment in question. They develop a stylized, but illustrative, game theoretic model showing a case in which fluid property rights – claim jumping and a lack of third-party enforcement of rights – exist in

[9] Brown (1964) argues that 'economic defendability' is key to animal territoriality, and in some respects his argument presages that of Demsetz (1967). Territoriality is better established where the costs of defense are lower.
[10] Rules of plunder have been documented elsewhere. Leeson (2009) describes the *Leges Marchiarum* that developed along the Anglo-Scottish border to regulate (but not to prevent) pillaging, feuding, and warfare.

equilibrium because of the search/race aspect of gold exploitation. This pattern emerged not because of norms of fairness, as suggested by Zerbe and Anderson (2001) – although some such norms may be implied by the details of settlement procedures adopted by miners and modeled here – but because the rules are self-enforcing given the nature of gold finds. (McDowell 2004)

Similar arguments have been made elsewhere: Baker (2003) follows the same logic, showing that different self-enforcing property rights arrangements will emerge for land with renewable resources depending on the density and predictability of yields. Ellickson (1989) analyzes the case of rules of capture in the Atlantic whaling industry of the 19th century and shows that the rules for establishing property rights to whales differed by species, depending on the difficulty of capturing each type of whale. The easier a whale was to capture, the more onerous the conditions of establishing and maintaining ownership.[11] Cheung (1970) suggests that non-migratory fishery resources will be more likely subject to private property protection than migratory resources because increased predictability ensures that enforcement costs will be lower, and Littlefield (1983) argues that water rights will be allocated according to either first possession (use) or geographic proximity to the source depending on the primary uses of a given water source.[12] Following these arguments, I develop a simulation to explore how property rights in various resources emerge in a dynamic, interactive environment.[13]

III. Simulating the Emergence of Property Rights to Land

Agent-based simulation allows one to observe the system-wide outcomes that emerge from local interaction of individual strategies, and evolutionary processes provide a means of assessing and comparing the viability of various strategies and conventions over time (Axelrod 1986, 1997, Skyrms 2004). If the model captures the relevant features of the real-world system in

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[11] Wilson, Jaworski, Schurter and Smyth (2010) find support for Ellickson's observations in the laboratory.

[12] Other research has emphasized the role of population size in determining the structure of property. Annen (2006) shows how the size of a population affects the choice of assignment rules for property rights over resources and attempts to explain the history of property in agricultural land via changes in population. While he takes the view that a Hobbesian assignment by conflict is the basic state of the world, he shows that for some populations, "rule-based" or conventional assignment may occur to avoid the rising costs of conflict. Although he claims to remain agnostic on the content of the assignment rules, his prediction that a convention will emerge at some population size and not at others is testable. Field (1989) also attempts to explain changes in property rights over land by changes in population. He argues that tradeoffs in the growth rates of transactions and exclusion costs due to growing population guide the archaeologically documented three-stage evolution from private holdings established by conflict to common property and back to private holdings. Maher and Lott (2000) find similar evidence for the effect of population density among non-human species.

[13] Other examples of this methodology include: Howitt and Clower's (2001) model of emergent commodity money and Puffert's (2002) study of standardization of railroad track gauge. Hodgson and Knudsen (2008) explain the governmental establishment of property rights in an agent-based framework.

question, the emergent strategy composition of the population (which may converge to a single convention or consist of a mixture of types) can be said to be ecologically rational for the economic system in the sense of Smith (2003). Hence, the emergent property rights structure that evolves in an appropriately specified model of the California Gold Rush should be that structure which is appropriate to, or ecologically rational for, a Gold Rush environment, and similarly for the structure that evolves in a model with a lower variance or renewable resource.

The intuition of the Clay and Wright (2005) model – that fluid property rights emerge for high-variance, exhaustible resources – is the starting point for the simulations reported here. In the following pages I develop and analyze the results of an evolutionary agent-based model that examines the conclusions of their theory in the context of a simulated gold rush, bounded by an artificial geography and informed by various details of historical circumstances in the California Gold Rush. I analyze their specific claim that property rights in a gold rush environment will be relatively *fluid*, and I explore the counterfactual claim that property rights will be more *stable* when the resource is more evenly distributed. Agent strategies are defined by a set of rules for invasion, self-defense, and third-party enforcement, and virtual natural selection favors those strategies that are most successful. Hence property rights are more stable when invasion is less and disputing and third-party enforcement are more prevalent.

After exploring the effects of variations in the distribution of a non-renewable resource, I extend the model to understand how the content of property rights changes with the economic environment more generally. Specifically, I develop treatments to compare the impact of (1) resource renewability and (2) increased scarcity on the development of property rights. With a renewable resource, the economic system takes on characteristics of a hunter-gatherer society, and the variance of claim yields does not diminish with extraction. Hence, under renewability, the effects of resource variance should be magnified relative to the exhaustible resource case. On the other hand, increased scarcity makes high-yield areas relatively more valuable and should make invasion more attractive, and since fewer claims will provide yields sufficient to cover costs of living, scarcity should induce a decrease in property protection. Table 1 below contains hypotheses on the impact of each of the treatment variations on the relative prevalence of each norm in the agent population compared to their prevalence in the baseline case with an exhaustible, high-variance, relatively abundant resource.

While the historical evidence is suggestive, simulation studies augment our understanding of economic *process*. The additional control available over decision rules and the economic environments for resource systems *in silico* increases the precision of data, and low cost replicability permits experimentation. Furthermore, the ability to engage in counterfactuals, exploring resource systems that have not been observed empirically, permits more accurate mapping of differences in resources to differences in rights.

III.A. Model Overview

The pseudocode below provides a general overview of the model. The following sections describe the economic system and the actions taken by agents in each period. The model is broken into three segments or loops over the set of agents in each period, one for immigration and search, one for resource extraction and decision rule updating, and one for emigration and replacement. Each section describes one segment of the model and is accompanied by additional pseudocode that provides further details to give the curious reader comprehensive insight into how the agents interact to develop property rights.

Model Pseudocode

```
Set Global Parameters
Initialize Land
Initialize Agents
Begin Loop Over Periods
    Begin Period
        Loop 1 – Migration and Search
        Loop 2 – Resource Extraction and Search Probability Adjustment
        Loop 3 – Emigration and Replacement
    End Period
    Record Data
End Loop Over Periods
```

III.B. Model Setup

Before each run of the model, a number of global parameters are instantiated to set up the model and specify the treatment. LOW_VARIANCE determines whether the resource is distributed with high or low variance, RENEWABLE determines whether the resource stock depletes when extracted, and SCARCITY determines the relative scarcity of the resource.

Each simulation lasts for T=15 periods and takes place on a 50x50 torus of *claims* which I will refer to as California. All claims possess two state variables that I will refer to throughout this discussion: *owned* and *occupied*. When an agent moves to a claim, that claim becomes both owned and occupied. However, if the agent moves to another claim, the original claim is still owned but is no longer occupied. Additionally, each claim is endowed with a certain stock of a resource, *g*. The distribution of *g* over the claims is unknown to the agents and varies with the treatment. In the LOW_VARIANCE treatment, *g* is distributed evenly across the claims; otherwise, as shown in Figure 1 below, *g* has a discrete distribution with density derived from empirical yields recorded during the California Gold Rush. The distribution is such that the total quantity of *g* is equal in both treatments, but variance is 0 in the LOW_VARIANCE treatment and extremely high otherwise. Finally, each claim has an associated extraction rate that specifies how much of the stock is extracted by an agent in each attempt.

N = 2000 *agents* begin each simulation with equal endowments of the resource denominated in units *g*. Any additional units of *g* that an agent acquires are added to that agent's endowment, but each agent must also pay a living cost in each period and may incur costs in disputes over ownership and occupancy of claims. Doubling each agent's living cost induces relative SCARCITY. Agents are also endowed with an initial probability of searching for a higher-yield claim. This probability updates in response to an agent's earnings and the costs it incurs in each period. Finally, agents possess a "normative DNA" consisting of three Boolean variables that represent their willingness to engage in *invasion*, *self-defense*, and *third-party enforcement*. Hence, any agent will be one of 2^3 agent types, and the distribution of these genetic types in the population will describe the property rights structure at any given time. The pseudocode below shows the initial values of global, land, and agent parameters.

Setup Pseudocode

```
Set Global Parameters
    LOW_VARIANCE = True or False
    RENEWABLE = True or False
    SCARCITY = True or False
    Search Probability Increment (δ = 0.01)
    #_OF_PERIODS (T = 15)
    #_OF_AGENTS (N = 2000)

Initialize California
    Loop Over Claims (k ∈ K)
        Set Owned = False
        Set Occupied = False
        Set Resource Stock (g_{k,t})
            If LOW_VARIANCE = True
                g_{k,t} = 80
            Else
                g_{k,t} ~ G(80, 250464) – See Figure 1.
                    G extrapolates from empirical yields reported in Clark (1970).
            End If
```

If RENEWABLE = *True*

$g_{k,t} = g_{k,t} * 0.5$

End If

Set Extraction Rate ($r_k = r^* = 0.2$)

End Loop Over Claims

Initialize Agents

Loop Over Agents ($i \in I$)

Set Endowment ($e_i = 40$)

Set Cost of Living per Period

If SCARCITY = *True*

$c_i = c^* = 16$

Else

$c_i = c^* = 8$

End If

Set Cost per Dispute/Enforcement ($d_i = d^* = 4$)

Set Cost per Unit Movement ($u_i = u^* = 1$)

Set Probability of Searching ($s_i = s^* = 0.5$)

Set Moving Costs ($m_{i,t} = 0$)

Set Dispute Costs ($f_{i,t} = 0$)

Set Boolean Norms:

Invasion:

INVADE ~ $B(1, 0.5)$

Self-Defense:

DISPUTE ~ $B(1, 0.5)$

3rd-Party Enforcement:

ENFORCE~ $B(1, 0.5)$

End Loop Over Agents

After the model is initialized, the first period begins. All agents migrate to a randomly selected, unoccupied claim in California. They extract gold from their claims, pay their costs of living, and update their probabilities of moving to a new claim based on their costs and earnings. For all subsequent periods, the model consists of three loops over the set of agents.

III.B. Loop 1 – Immigration and Search

In the first loop, those agents that are not in California migrate to an unoccupied claim, and those agents already in California decide whether or not to search for a higher-yield claim than the one they currently occupy. If an agent, *i*, decides to search for a new claim, it selects a random claim, *k*, in its Moore neighborhood and attempts to move onto that claim. Each agent's normative DNA then determines how it will behave with respect to the claim in question.

If the claim is owned or occupied, only agents that are willing to invade (INVADE = *True*) will continue their attempt to move. If an agent goes forward with an attempt to invade, the owner, *j*, of the claim being invaded then decides whether or not to defend the claim. If the owner will not defend its claim (DEFENSE = *False*), then the owner retreats and the invader becomes the new owner. On the other hand, if the owner is willing to defend the claim, both invader and owner poll their neighbors to find those that are willing to engage in third-party enforcement (ENFORCE = *True*). Enforcing agents take the side of invaders if they would be willing to invade a claim themselves, and they take the side of owners if they are unwilling to invade. Disputes are settled by majority rule, and ties are broken randomly.[14] All parties to any dispute pay a cost of disputing, d, (representing resources expended in settling the dispute), but invaders record these as moving costs, m, while enforcers and defenders record them as enforcement costs, f.

If an agent faces invasion and loses a claim that it currently occupies, then that agent retreats, either to another claim that it owns or to an un-owned claim nearby. When agents move, they pay a cost of moving, u, multiplied by the distance of the new claim from their original location. Hence retreating agents that cannot find a nearby unoccupied claim may be forced to pay high costs of moving. If the cost of moving exceeds the agent's endowment, that agent expends the rest of its endowment and will leave California in Loop 3. The pseudocode below details the process by which agents migrate and search for new claims.

Immigration and Search Pseudocode

```
Begin Loop 1 – Immigration and Search
    If Agent i is NOT in California
    .   Migrate to California
    .       Move to an Unoccupied Claim k
    Else If Agent i is in California
    .   Decide Whether to Stay on Current Claim or Search
    .       If runif(0,1) > s_{i,t}
    .           Search = True
    .       Else
    .           Search = False
    .       End If
    .   If Search = True
    .   .   Move to New Claim
    .   .       Randomly Choose one Claim k in Moore Neighborhood
    .   .   If Claim is Owned by Another Agent j
    .   .   .   Decide Whether to Invade Owned Claim
    .   .   .   If i_INVADE = True
    .   .   .   .   If Claim is Adjacent to j
    .   .   .   .   .   Decide Whether to Dispute Claim
    .   .   .   .   .   If j_DISPUTE = True
    .   .   .   .   .   .   i and j Pay Dispute Cost and Record d_i (m_{i,t} = m_{i,t} + d_i)
    .   .   .   .   .   .   Poll Neighbors of i and j to Settle Dispute
    .   .   .   .   .   .   Loop Over Moore Neighborhood of i and j to get Neighbors nei
    .   .   .   .   .   .   .   If nei_ENFORCE = True
    .   .   .   .   .   .   .   .   Pay Dispute Cost and Record d_nei (f_{nei,t} = f_{nei,t} + d_nei)
```

[14] Zerbe and Anderson (2001) and Pisani (1998/99) cite the common cultural heritage and affinity for democracy as an explanation of the relative lack of violence in settling disputes during the Gold Rush. The mechanism here reflects that common cultural heritage and is maintained throughout the variations of the model.

. . . . *If* nei_{INVADE} = *True*
. . . . SupportInvader++
. . . . *Else*
. . . . SupportOwner++
. . . . *End If*
. . . . *End If*
. . . . . . End Loop Over Neighborhood
. . . . . . Majority Rules
. . . . . . Ties Broken Randomly
. . . . . . *If* SupportInvader > SupportOwner
. . . . . . *i* Wins
. . . . . . *Else If* SupportInvader < SupportOwner
. . . . . . *j* Wins
. . . . . . *End If*
. . . . . *Else If* $j_{DISPUTE}$ = *False*
. . . . . . *i* Wins
. . . . . *End If*
. . . . *Else If* Claim is NOT Adjacent to *j*
. . . . . *i* Wins
. . . . *End If*
. . . *Else If* INVADE = *False*
. . . . *j* Wins
. . . *End If*
. . *Else If* Claim is NOT Owned by Another Agent
. . . *i* Wins
. . *End If*
. .
. . *If i* Wins
. . . *i* Moves to *k*
. . . $s_{i,t+1} = 0.5$
. . . *j* Loses Claim
. . . *If j* Is Removed from Claim
. . . Retreat to Old Claim or Un-owned Claim Nearby
. . . $s_{j,t+1} = 0.5$
. . . Pay Moving Cost (u_i)
. . . $m_{i,t} = m_{i,t} + u_i*distance$
. . . *End If*
. . *Else If j* Wins
. . . *i* Stays
. . . *j* Keeps Claim
. . *End If*
. *End If*
End If
End Loop 1

III.C. Loop 2 – Resource Extraction and Search Probability Adjustment

After agents have moved onto claims, each agent in California extracts resources from the claim it currently occupies to generate income, *y*. Each piece of land has an extraction rate, *r*, which indicates what percent of the resource stock, *g,* an agent extracts in each period. When the resource is exhaustible, claims deplete exponentially because the stock on any given claim in the next period is reduced by the amount extracted in the current period. Resources extracted are added to the agent's endowment, *e*. Then agents pay their costs of living (*c*), moving (*m*), and enforcing (*f*) by subtracting these costs from their individual endowments.

Next, each agent updates its probability of searching for a higher-yield claim. For each unit of income and incurred costs of moving or attempting to move, an agent decreases its probability of searching in the subsequent period by δ, and for each unit of living cost and enforcement cost, an agent increases its probability of moving in the subsequent period by δ. The intuition is that agents are more likely to stay on high-yield claims and on those from which attempting to move is costly and less likely to stay on low-yield claims and claims on which they incur large enforcement costs. The pseudocode below details the extraction and updating process.

Resource Extraction and Search Probability Adjustment Pseudocode

```
Begin Loop 2 – Resource Extraction and Search Probability Adjustment
    If Agent is in California
        Extract Resources from Land to Produce Income (y_{i,t} = r_k * g_{k,t})
            If RENEWABLE = False
                g_{k,t+1} = g_{k,t} – y_{i,t}
            End If
        Pay Cost of Living (c_i), Moving (m_{i,t}), and Enforcing (d_{i,t})
            Update Endowment
                e_{i,t+1} = e_{i,t} + y_{i,t} – c_i – m_{i,t} – d_{i,t}
        Update Probability of Search
            s_{i,t+1} = s_{i,t} + δ * (c_i + d_i – y_{i,t} – m_{i,t})
    End If
End Loop 2
```

III.D. Loop 3 – Emigration and Replacement

Finally, some agents may acquire insufficient income to cover their costs of living, moving and disputing. If an agent's endowment falls to 0, that agent leaves California and is replaced by a new agent. New agents are instantiated as in the model setup, with the same initial endowment, probability of searching, and costs. However, new agents' adopt their norms based on the probability of observing each norm in the population. Hence, if 60% of agents have INVADE = *True*, then a new agent will have INVADE = *True* with probability 0.6. Again, the pseudocode below details this process.

Emigration and Replacement Pseudocode

```
Begin Loop 3 – Emigration and Replacement
    If e_{i,t+1} ≤ 0
        Leave California
            Abandon Claims
        Replace Departed Agents with New Agents
            Initialize New Agents as in Model Setup Pseudocode Except
                Replace with Norms Drawn from Empirical Distribution in Population
    End If
```

End Loop 3

IV. Results and Analysis

Table 2 below lists the eight simulation treatments. To test the hypotheses from Table 1, I run 100 simulations of each treatment. The n^{th} simulation in each treatment receives the same seed in its random number generator to minimize the impact of computer-generated randomness across the treatments. Figure 2 displays the average proportion of agents in each treatment that follow each norm after 15 simulation periods. In general, the data suggest that relatively abundant resources will tend to increase both Invasion and Self-Defense, and low variance resource distribution decreases the rate of Enforcement. Otherwise, at this level of analysis, the effects of the variables are interdependent and unclear. Hence, I perform regression analysis to identify the treatment effects while controlling for potential confounds.

IV.A. Regression Analysis

Using all 100 runs of each treatment in the non-genetic case, I construct a dataset to identify treatment effects on the proportion of the population in each simulation run that is willing to invade (V_t), defend (W_t), and third-party enforce (X_t). Dichotomous dummy variables for LOW_VARIANCE (L), RENEWABLE (R), SCARCITY (S), and their interactions capture these effects after I control for the strategy composition of the population and path dependence. I estimate the following equations with ordinary least squares ($R^2 = 0.93$):[15]

(1) $V_t = \alpha_0 + \alpha_L L + \alpha_R R + \alpha_S S + \alpha_{LR} LR + \alpha_{LS} LS + \alpha_{RS} RS + \varepsilon$

(2) $W_t = \beta_0 + \beta_L L + \beta_R R + \beta_S S + \beta_{LR} LR + \beta_{LS} LS + \beta_{RS} RS + \varepsilon$

(3) $X_t = \gamma_0 + \gamma_L L + \gamma_R R + \gamma_S S + \gamma_{LR} LR + \gamma_{LS} LS + \gamma_{RS} RS + \varepsilon$

Table 3 reports the results of the regressions. Note that 7 of the 9 coefficients on treatment variables have the predicted sign but only 5 are significant. The findings below summarize what can be learned about the treatment effects from the regressions.

Finding 1: For Equation (1), the estimated coefficient on Low Variance distribution is negative and significant, and the coefficient on Scarcity is positive and significant. However, while the coefficient on Renewability has the predicted sign, it is not significant.

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[15] For path dependence, each equation's RHS also includes a lagged value of the proportion of agents with the norm on the LHS and the interaction of this variable with the treatment dummy variables. I control for the strategy composition by including variables on the RHS for the percent of the population with each *other* norm = *True* and the interactions of these variables with the treatments. Finally, I also include interactions between the treatments and the amount of the resource extracted in a given period (with the exception of R because of matrix singularities).

As hypothesized, a more even resource distribution is associated with decreased prevalence of the Invasion norm in the agent population. Because there is less to be gained by invading the claims of other agents (since no claim is likely to be worth noticeably more than any other), and because invasion is costly, a more even resource distribution reduces the effectiveness of invasion. Resource renewability, which means that the variance of claim yields does not decrease with extraction, also appears to decrease the amount of invasion, but the effect is not significant. However, the interaction between renewability and low variance is negative and significant, supporting the argument that when claim yields are equal invasion will be less common.

On the other hand, scarcity is associated with an increase in the prevalence of the Invasion norm. With an increase in relative scarcity, fewer claims are capable of supporting an agent. Hence, there is more incentive for agents to invade in hopes of acquiring higher-yield claims. The negative and significant coefficient on the interaction of renewability and scarcity supports this argument because renewability implies that the number of claims capable of supporting an agent does not diminish with extraction.

Finding 2: In equation (2), the estimated coefficients on Low Variance distribution, Renewability, and Scarcity are all positive and significant.

A more an equal distribution has a positive impact on the rate at which agents defend their claims because the costs of being moved off of one's claim exceed the potential benefits of moving to a new claim when variance is low. Furthermore, resource renewability also increases the prevalence of the self-defense norm. When the resource is renewable, the incentive to defend a high-yield claim remains high throughout a simulation because the yield does not diminish with extraction. Hence, those agents willing to defend claims will be more likely to survive over time. A positive (but insignificant) coefficient on the interaction of low variance and renewability also supports these arguments.

Surprisingly, however, scarcity also increases the rate of self-defense relative to the baseline. This effect likely stems from the fact that successful agents must defend the few claims with sufficient yields to cover the costs of living. However, when the resource is low variance, *any* claim from which agents have extracted sufficient resources becomes unable to support agents under scarcity. Thus, the coefficient on the interaction between scarcity and low variance distribution is significant and negative.

Finding 3: In equation (3), the estimated coefficient on Low Variance distribution is positive and significant. The coefficients on Renewability and Scarcity are both negative but only that on Renewability is significant.

As expected, low variance distribution increases the willingness of agents to engage in third-party enforcement. When resources are distributed unevenly, few agents survive that are willing to engage in third-party enforcement because the relatively high rates of invasion force agents to engage in large amounts of third-party enforcement. However, while scarcity has the predicted negative sign, its effect on the prevalence of third-party enforcement is insignificant. Surprisingly, renewability actually reduces the prevalence of enforcement among the agents.

The results above are suggestive as to the short run impact of each treatment variable on the relative effectiveness of various agent norms and the property rights arrangements that emerge from their interaction. As expected, an agent's likelihood of invading another agent's claim (i.e. violating rights to property) is lower when the resource in question is evenly distributed, and its likelihood of defending or enforcing is higher. Resource renewability tends to lead to more secure rights to property in that agents invade less and engage in greater amounts of self-defense; however, renewability actually decreases the rate of third-party enforcement. Finally, scarcity strongly increases the rate of conflict in the population because it increases both willingness to invade and willingness to fight.

IV.B. The Effects of Norm Heritability

Since these results speak only to the outcomes after a single generation of the model, we still lack a sense of the evolutionary stability of the various norms. To explore the long-term impact of evolutionary pressures on the effectiveness of norms, I run 10 sets of 10 overlapping-generations simulations for each of the 8 treatments to observe how replicator dynamics impact the evolution of strategies across generations. Agents in simulation $n+1$ are instantiated with norms drawn from the observed probabilities in the final period of simulation n.

Figure 3 shows the average proportion of agents with each norm = *True* after 5 generations of the model with heritable norms. The strongest effect comes from resource abundance. When resources are relatively abundant, the prevalence of self-defense is noticeably higher after 5 generations. Other treatment effects are less clear or admit of exceptions. For example, invasion is more common with high variance under scarcity, but under abundance, the higher rates of invasion occur under low variance. Furthermore, enforcement is relatively prevalent under high variance, but the most striking fact about enforcement is that its prevalence tends toward zero in all treatments. This effect may result from the fact that engaging in enforcement is costly and does not influence the probability of others engaging in enforcement on an agent's behalf. Furthermore, since agents enforce their own invasion norm and are not able to be inconsistent, there may be perverse effects whereby agents who enforce the rights on invaders increase the probability that they are invaded in the future. One possible method of exploring these possibilities is discussed in the summary below.

Figure 4 displays the proportion of agents willing to invade, self-defend, and enforce after 10 iterations of the genetic model. As after 5 generations, the most noticeable impact is that of relative abundance on the rate of self-defense. The starkest treatment effect is between abundance and scarcity when the resources are low variance and renewable. In the abundant case, property rights are at their most insecure, with high rates of invasion and self-defense, but in the scarce case, property rights are implicitly almost perfectly respected since invasion has fallen nearly to zero.

Figure 5 displays the change in prevalence of each norm from 5 to 10 generations. I subtract the proportion of agents with each norm = *True* in the 5th generation from that same proportion in the 10th generation. When we move from 5 generations to 10, the rate of invasion falls in every treatment with abundant resources. Thus property rights tend to become more secure over time with relative abundance; this effect is even stronger for abundant, low variance resources because self-defense increases while invasion falls. On the other hand, with scarcity the rate of invasion falls only for those treatments with low variance resources. With scarce, high variance resources, property actually becomes less secure because self-defense falls as invasion rises.

V. Discussion and Conclusions

Thus I find support for the basic claims of the theoretical treatments discussed above. Property rights structures adjust in response to ecological variables in consistent and predictable ways. Increasing scarcity generally weakens respect for property (except for the extreme case of low variance, renewable resources), and low variance in resource distribution has the opposite effect. These results support that claim that the relative fluidity of property rights in the California Gold Rush stemmed not from the failure or absence of government structures, but rather from the characteristics of the sought-after resource. The counterfactual examples, wherein strong support for property rights emerges under other resource characteristics provide further evidence of this claim. Surprisingly, third-party enforcement is relatively uncommon in all treatments. Since this could be due to perverse incentives created by enforcing on behalf of one's own invasion norm, subsequent versions of the model will need to take additional behavioral possibilities into account, such as permitting agents that invade but also defend the claims of their neighbors against other invaders (an ethnocentric strategy a la Hammond and Axelrod 2006).

Numerous interesting questions suggest possible extensions of this model. For example, since the resource distributions herein are relatively extreme cases, how robust are these data to more moderate distributions? Or, how might cultural transmission change the evolutionary outcomes of the model? If agents slowly become more like their neighbors (by copying one trait at random from a random neighbor as in Axelrod (1997) or by copying their wealthiest neighbor), will convergence to the patterns observed above be expedited or will the outcome differ? What other games of conflict from the literature in economics, biology and political science might be substituted for the majority rule mechanism applied herein? And how might emergent property rights be altered if agents were less behaviorally naïve in terms of search or willingness to defend their own and others' claims? Strategic search in which agents employ some form of expected utility computation and strategic defense in the form of conditional cooperation could have a large potential impact on model outcomes. Or, rather than employing Boolean norms, agents might claim jump, defend, and enforce probabilistically. The possibilities are endless. All of these questions merit study, and it will be important to explore these possibilities to ensure that the theory of property rights and resource characteristics herein is robust to such variations.

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Table 1: Hypotheses on Effects of Ecological Variables Relative to Gold Rush

	Invasion	*Self-Defense*	*3rd-Party Enforcement*
Low Variance	–	+	+
Renewable	–	+	+
Scarcity	+	–	–

Table 2: Simulation Treatments

	Low Variance	*Renewable*	*Scarcity*
Gold Rush			
Counterfactual	X		
Hunter-Gatherer HV		X	
Hunter-Gatherer LV	X	X	
Gold Rush S			X
Counterfactual S	X		X
Hunter-Gatherer HV S		X	X
Hunter-Gatherer LV S	X	X	X

Table 3: Treatment Effect Estimates from OLS Equations (1-3)

	Invasion$_t$	*Self-Defense$_t$*	*3rd-Party Enf$_t$*
Low Variance	**-0.032*** **	**0.014** **	**0.035*** **
Renewable	**-2.59e-03**	**0.026*** **	-0.062***
Scarce	**0.061*** **	0.090***	**-0.012**
L*R	-6.88e-03***	1.07e-03	1.90e-03
L*S	1.08e-03	-1.37e-03*	-0.011***
R*S	-4.50e-03***	-7.46e-03***	-1.97e-03

*** Significant at the 99.9% level of confidence.
** Significant at the 99% level of confidence.
* Significant at the 95% level of confidence.
Bolded entries have the hypothesized sign.

Figure 1: Resource Distribution
High Variance Treatment

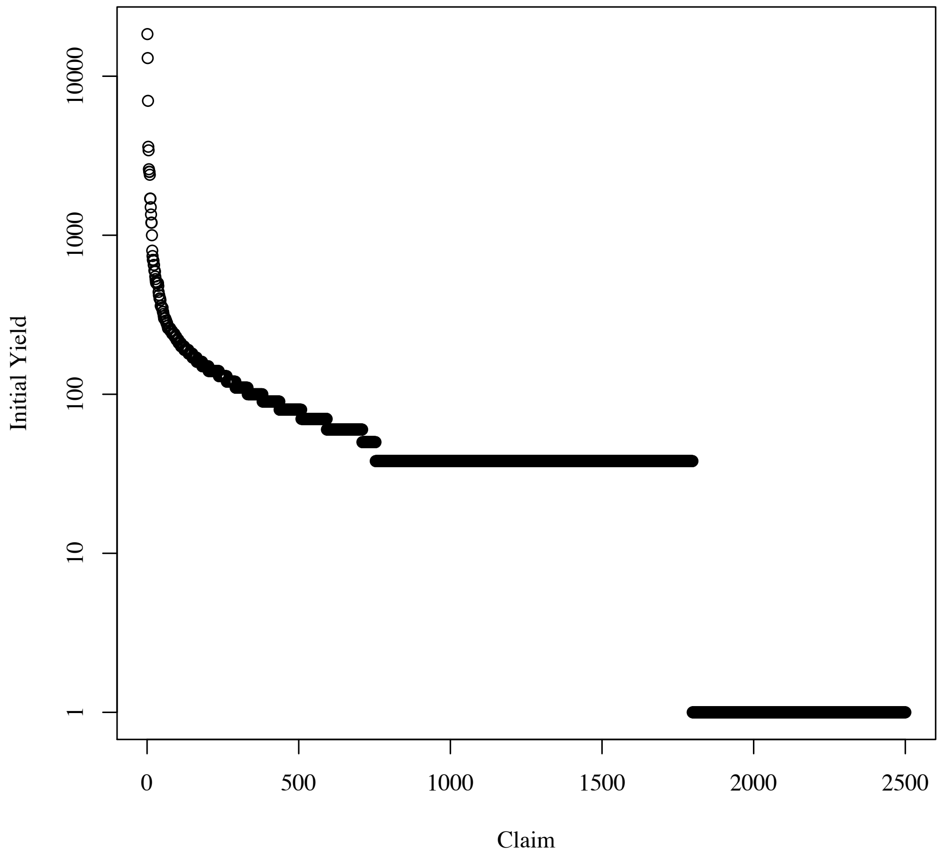

Figure 2: Evolved Agent Norms after 1 Generation
by Treatment

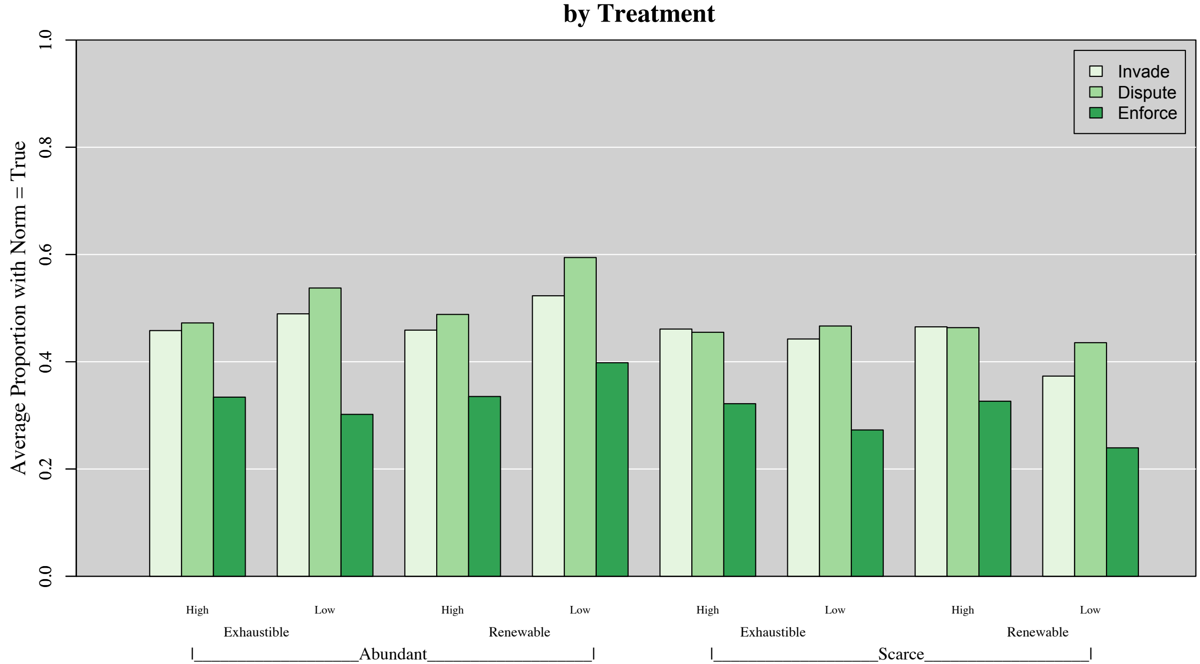

Figure 3: Evolved Agent Norms after 5 Generations by Treatment

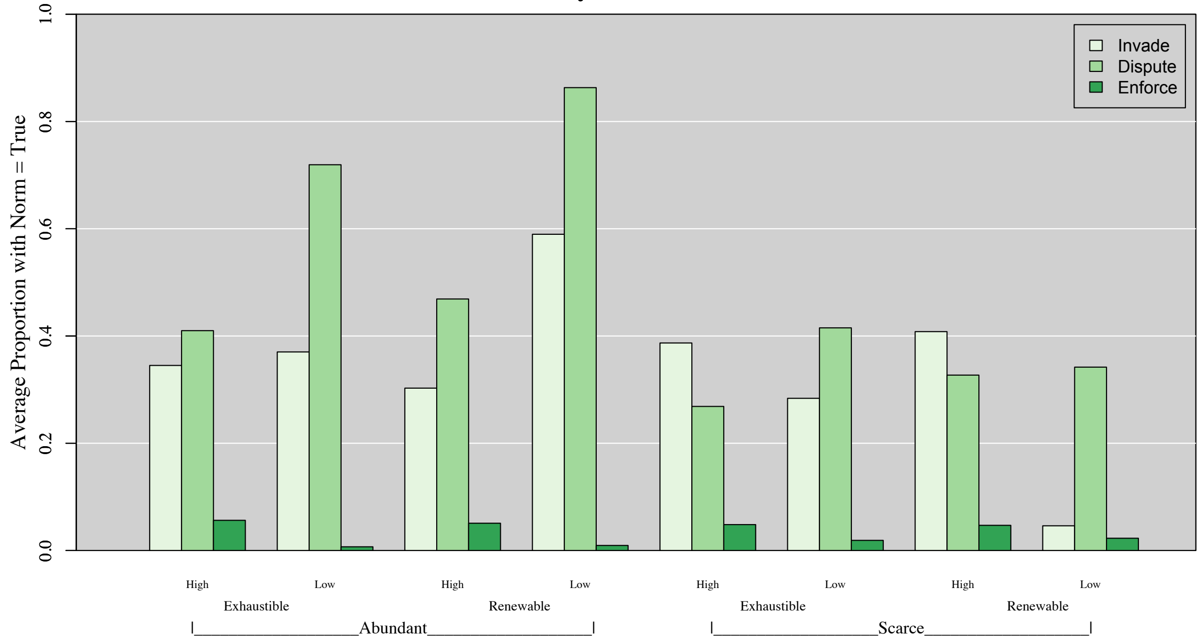

Figure 4: Evolved Agent Norms after 10 Generations by Treatment

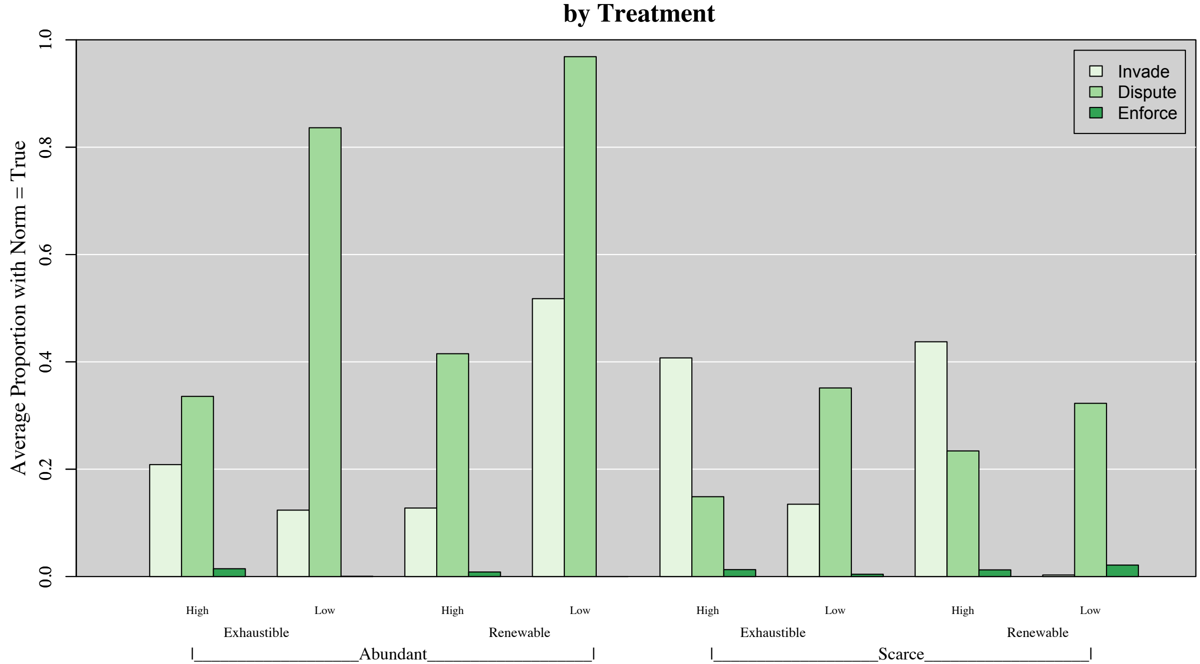

Figure 5: Change in Evolved Agent Norms from 5 to 10 Generations by Treatment