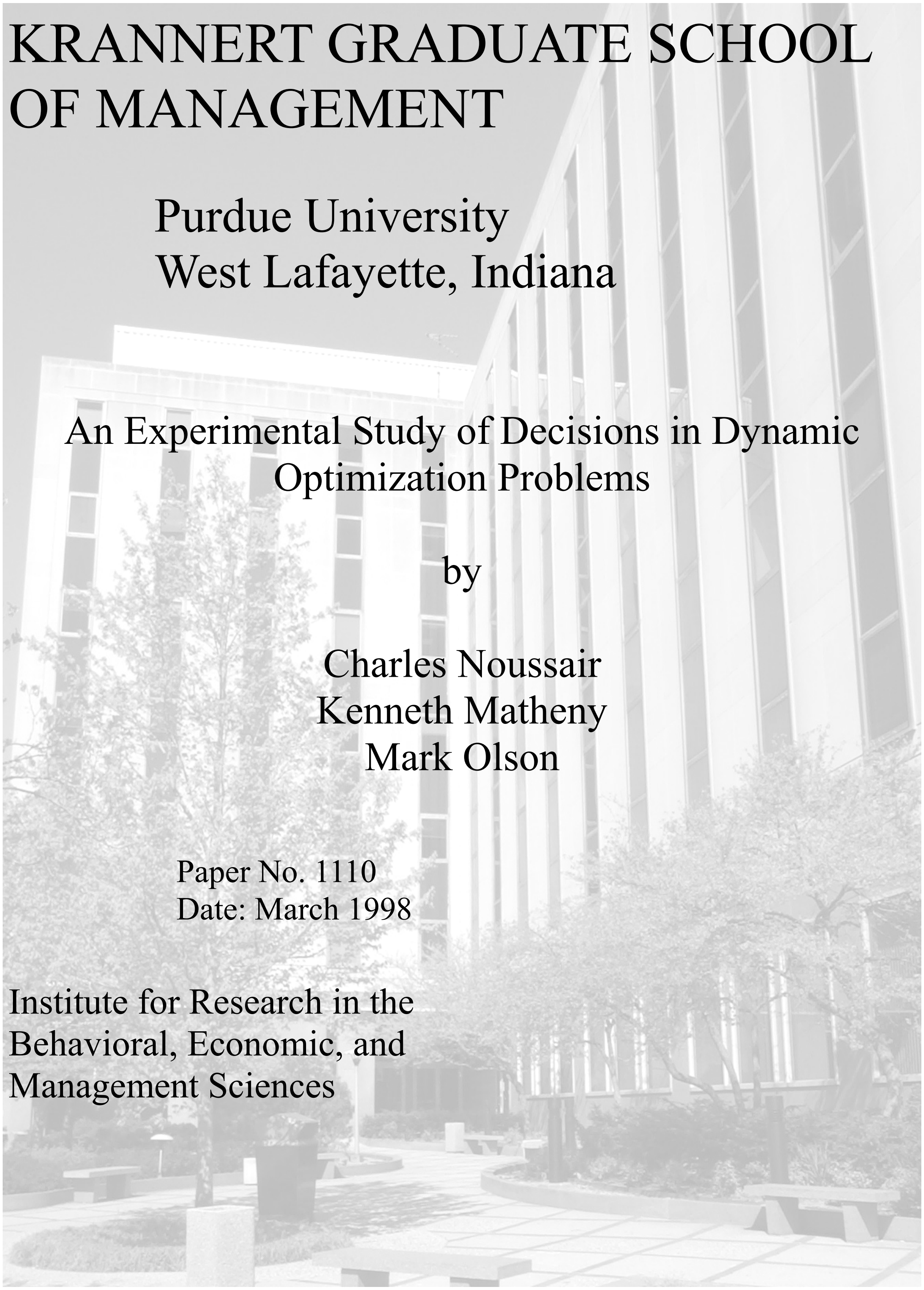

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An Experimental Study of Decisions in Dynamic Optimization Problems

by

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1 Introduction

The concept of dynamic decision making is fundamental to much of modern macroeconomics. An understanding of the link between current decisions and future outcomes is crucial for the analysis of economic growth, the role of saving and investment, the properties of asset markets, and other important topics. Many macroeconomic models focus on the outcomes of optimal behavior of agents and therefore assume that agents are able to solve dynamic decision problems which may be very complex. Economists have devoted much attention to mathematical techniques for solving such problems and the research has yielded many important insights into the nature of economic activity. The rapid development of optimization techniques to solve theoretical models has outpaced the empirical study of the actual decisions made by human

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agents in the setting of the models.

One method of providing empirical tests of macroeconomic models is to use field data. However, though theoretical models are often motivated by phenomena observed in the field, they often do not (and we would argue that they should not) model field economies precisely. Therefore, data generated in the field often do not provide the optimal arena for testing of models. Difficulties in using field data for the testing of macroeconomic theories include the following. (1) Economies with the exact structure of stylized economic models are usually difficult to find in the field. (2) There is a limited amount of field data available, and the researcher is unable to generate data repeatedly under identical conditions. (3) The researcher is restricted to the particular values of the variables which happen to occur naturally, making it difficult to evaluate theoretical predictions about comparative statics or dynamics, or to compare the predictions of two or more alternative theories. (4) Some of the important variables are not observable to the researcher at all, making it difficult to determine what the theoretical predictions actually are.

However, using experimental methods, it is possible to construct economies that overcome these data problems. The exact structure of the model of interest can be reproduced. A large number of independent economies can be constructed, so that as much data as needed can be collected. The values of the parameters in the economy can be manipulated, allowing propositions about comparative statics and dynamics to be carefully evaluated, and the predictions of competing theories to be clearly distinguishible from each other. Variables which are unobservable in the field, can be observed in the experimental economy by the researcher. The experimental economies can be designed with the sole purpose of generating data that can be compared to theoretical predictions.

In this paper we use an experimental approach to study the decisions of human subjects who are given cash incentives to solve a particular representative agent dynamic model widely studied in macroeconomics. In a representative agent dynamic model, an economy is modelled as a single decision maker, who maximizes the discounted utility of consumption over the appropriate time horizon. The assumption of a single decision maker in the economy removes complications resulting from the existence of multiple agents, such as inefficiencies resulting from strategic behavior or externalities, and technical difficulties arising from the aggregation of preferences. The particular problem we consider was first studied by Ramsey (1928), and later by Cass (1965) and Koopmans (1965). In the model, there is a single agent in a one-sector, closed economy with concave production and utility functions. The agent maximizes utility over an infinite horizon, starting with an initial level of savings in the form of physical capital. Capital is used to produce output, which is either consumed or invested in augmenting the capital stock used in future production. If the agent follows the optimal decision path, the economy's capital stock converges asymptotically to an optimal steady state level.

This paper reports the data from an experiment which reproduces the structure of the theoretical model, using a cash payment structure to create the incentives which exist in the model.[1] The experimental design is organized into a *basic design* which has two factors and two levels of each factor, and two extensions of the basic design. In the basic design, there are two levels of initial endowment of capital stock, one higher than the optimal steady state level of capital and one below. Along the optimal decision path convergence to the optimal steady state is from above in the high endowment treatment and from below in the low endowment treatment. There are also two different production functions which are used. Varying the production function changes the speed of convergence of the capital stock to the optimal steady state level along the optimal trajectory.

In addition, we add two treatments to the basic design to address two important methodological issues. The first issue, which arises in studies like this one, is how to implement an infinite horizon model in the laboratory. We take two different approaches. In the basic design

[1] For two examples of the use of experimental methods in macroeconomics see Marimom and Sunder (1993), or Lian and Plott (1998).

we impose an exogenous constant probability of terminating the economy at each time t, which, under appropriate assumptions, is equivalent, from the point of view of the agent, to an infinite horizon situation with discounting. In the other approach, we terminate the economy at a fixed time T, which is known to the subjects in advance, discount the payoffs from time 1 until time T, and award the subjects the discounted value of the capital stock remaining after time T assuming they made optimal decisions from that point on. The optimal decision is exactly the same for the two implementations of the infinite horizon. We compare the two methods for one of the treatment cells of the basic design.

A second methodological issue which sometimes arises in experimental research is concern about the use of only one subject pool. The data from the basic design was generated by undergraduate students at Purdue University, in Indiana, located in the United States. As a check on the robustness of our results, for two of the treatment cells, we replicate our experiment using undergraduate students from Waseda University, located in Tokyo, Japan. A finding of no subject pool effect would strengthen our results in light of the considerable cultural difference between the two groups and popular views about differing intertemporal choice behavior between inhabitants of the two countries.

The data show that in some treatments, overconsumption relative to the optimum consistently occurs, and in the other treatments there is a tendency toward underconsumption. Whether or not subjects over-or underconsume depends on the production technology present in the economy. Moreover, the direction of deviations in consumption and capital stock from the optimum is not affected by the ending rule nor by the subject pool employed. We also find a tendency under all treatments toward sudden episodes of great overconsumption and depletion of capital stock, a phenomenon to which refer as a *binge*, rather than the pattern of consumption and investment smoothing over time suggested by the theoretical model.

The next section describes the theoretical model we are testing, section three describes the procedures of the experiment, section four lists the hypotheses tested, and sections five and six present the results of the study and our final thoughts.

2 Description of Theoretical Model

2.1 Model

In the theoretical model corresponding to our experiment, each agent is assumed to maximize the present discounted value of current and future utility given in equation (1), subject to a sequence of resource constraints as in equation (2) and a given strictly positive initial capital stock, k_0.

$$\max \sum_{t=0}^{\infty} (1+\rho)^{-t} u(c_t) \tag{1}$$

$$c_t + k_{t+1} \leq f(k_t) + (1-\delta)k_t, \qquad \forall t \geq 0. \tag{2}$$

Depreciation of the capital stock occurs at the rate $\delta \in (0, 1]$. Utility and production functions u and f are strictly increasing, concave, and differentiable. The subjective rate of time preference ρ is positive. These assumptions guarantee that (2) will hold with equality in every round t.

Necessary and sufficient conditions for optimal choices of consumptions and capital stocks include the Euler equation in (3), the transversality condition in (4), and (5), which is equivalent to (2) under the assumption of non-satiation.

$$u'(c_t) = (1+\rho)^{-1} \left[1 - \delta + f'(k_{t+1})\right] u'(c_{t+1}), \qquad \forall t \geq 0 \tag{3}$$

$$\lim_{t \to \infty} (1+\rho)^{-t} u'(c_t) k_{t+1} = 0 \tag{4}$$

$$k_{t+1} = f(k_t) + (1-\delta)k_t - c_t, \qquad \forall t \geq 0. \tag{5}$$

Equations (3) and (5) constitute a well-known nonlinear planar dynamical system in the capital stock and consumption.[2] The steady state solution is a time-invariant one where $c_t = \bar{c}$ and $k_{t+1} = \bar{k}$, $\forall t \geq 0$, satisfying

$$\bar{c} = f(\bar{k}) - \delta\bar{k} \tag{6}$$

$$f'(\bar{k}) = \rho + \delta. \tag{7}$$

The properties of the utility function (other than non-satiation) have no bearing on the single positive steady state. Assumptions on f guarantee that there is exactly one steady state with strictly positive capital and consumption. There is another steady state at the origin; however, that solution represents a permanent absence of activity.

[Figure 1: About Here]

The phase diagram in Figure 1 summarizes many properties of this dynamical system for any positive initial capital stock. The functions $G(k)$ and $H(k)$ are the phaselines for capital and consumption described in (8) and (9).

$$k_{t+1} \geq k_t \iff c_t \leq f(k_t) - \delta k_t \equiv G(k_t) \tag{8}$$

$$c_{t+1} \geq c_t \iff c_t \geq f(k_t) - \delta k_t + (k_t - \bar{k}) \equiv H(k_t). \tag{9}$$

The steady state $(\bar{k}, \bar{c})$ occurs at the intersection of these two phaselines. The steady state has the familiar saddlepoint property. Based on the phaselines, the positive orthant in Figure 1 can be subdivided into four regions. For all $(\hat{c}_t, \hat{k}_t)$ to the northwest or the southeast of the phaselines the system will diverge without ever returning towards the steady state $(\bar{c}, \bar{k})$. Indeed, there is only a one-dimensional manifold, denoted by $S(k_t)$, such that if (c_t, k_t) are on this manifold at some date $t \geq 0$, the system will converge monotonically to the steady state. Sequences of consumption and capital which are generated through $S(k_t)$ are the only ones satisfying (3)-(5)

[2] See for example Azariadis [1993, chapters 7 and 14].

which converge to the positive steady state. In theory, it is always possible for the system to remain on the stable manifold S in every round, including the initial round, because current consumption is a "free" or non-predetermined variable. In other words, given any $k_t > 0$, c_t can be chosen such that $c_t = S(k_t)$. Because sequences generated through S in this way satisfy (3)-(5), they are optimal.

A non-trivial question is the computation of $S(k_t)$, which is also the relationship between beginning-of-round capital and optimal consumption each round. Except in special cases it is generally difficult to compute S analytically. We use a shooting algorithm to approximate S to roughly 6 significant digits.[3] Figure 1 depicts the phase lines and stable manifold S for the following specification, which is one of the two used in our experiment:

$$u(c) = \eta \ln(\gamma + c) \tag{10}$$

$$f(k) = \phi k^{\alpha} \ . \tag{11}$$

where $\eta = 100, \gamma = 1, \rho = 1/9, \phi = 25.23, \alpha = 0.2$, and $\delta = 0.5$. In general different assumptions on the parameters affect optimal choices of c_t^* and k_{t+1}^* in as much as the former determine the properties of S.

2.2 Dynamical Properties

The solution to (3)-(5) has four well-known dynamical properties:

1. For any given initial capital stock, $k_0 \geq 0$, optimal sequences of consumption and capital are unique.

2. Convergence to the steady state is strictly monotonic whether $k_0 > \bar{k}$ or $k_0 < \bar{k}$. If $k_0 = \bar{k}$, then $(c_t, k_t) = (\bar{c}, \bar{k})$ every round beginning with round 0.

[3] The algorithm is similar to one used by King and Rebelo [1989]. *GAUSS* code is available on request.

3. Changes in the capital stock (net investment) are larger the further k_t is from the steady state.

4. The speed of convergence to the steady state and other dynamical properties are determined by the parameters, including α, δ, γ, and ρ. Changes in η and ϕ have no effect on convergence in proportional terms. ϕ matters mostly by shifting the scale of capital and consumption but is otherwise unimportant.

3 The Experiment

3.1 The Basic Design

The parameters for the basic design are given in Table 1. The design is a two-by-two design with two levels of initial capital stock, 3 and 50, and two different production functions, given in (12) and (13).

$$f^F(k_t) = 25.23 * k_t^{.2} \tag{12}$$

$$f^S(k_t) = 0.88 * k_t^{.9} \tag{13}$$

[Table 1: About Here]

The parameters are chosen so that all treatments have the same optimal steady state capital stock, $\bar{k} = 14$. Convergence to $\bar{k}$ is from above when $k_0 = 50$ and from below when $k_0 = 3$. We refer to the $k_0 = 3$ and $k_0 = 50$ treatments as the *Low* and *High* treatments respectively. k_t^H and k_t^L denote the capital stock holdings in round t under High endowment and Low endowment respectively. Convergence is predicted to be faster when $\alpha = .2$ than when $\alpha = .9$. Therefore, we refer to the $\alpha = .2$ and the $\alpha = .9$ treatments as the *Fast* and the *Slow* treatments respectively. $k_t^F, k_t^S, f^F(k_t)$ and $f^S(k_t)$ will refer to the capital stock holdings in round t and the production functions under Fast and Slow convergence. The depreciation rate was set to $\delta = .5$ and the discount rate to $\rho = 1/9$. The utility function used in all treatment cells is:

$$U(c_t) = 100 * ln(1 + c_t) \tag{14}$$

3.2 Implementation

The data were gathered in seven sessions. One of the sessions was conducted at Waseda University, Tokyo, Japan, and the rest of the sessions were conducted at Purdue University, Indiana, USA. As soon as subjects arrived for their session, they went through the instructions, which were computerized. The text of the instructions is given in the Appendix. After he completed the instructions, each subject solved one of the decision problems described above 23 times. We will refer to each of the attempts to solve the problem as a *period*, so that the experiment consisted of 23 periods, where each period corresponded to an "infinite" horizon. Each subject solved the same decision problem repeatedly for the entire session in which she participated.

In each of the treatments of the basic design, the *Random Ending Rule* was in effect. Under the Random Ending Rule, each period consisted of an uncertain number of rounds,[4] and the probability of the period terminating in the current round was 10 percent in every round. Each round corresponded to a time t in equations (12)-(14). The 10 percent probability of each round being the final round in a period induced a rate of time preference $\rho = 1/9$. The round at which a period would end was drawn randomly in advance from the appropriate distribution. The same random draws of period lengths were used for every subject to facilitate comparisons of data from different subjects and treatments. For example, period 18 for each subject in any of the *Random Ending Rule* treatments consisted of an identical number of rounds.

Since the model under investigation has a single representative agent, the decision situation

[4]The use of the terms *rounds* and *periods* in this manner may seem somewhat unusual to some readers. However, it seems more natural to us to think of each "infinite horizon" in the experiment as the relevant unit of time, and therefore we call each of these units a period.

was presented as an individual choice problem.[5] Each agent was her own economy, and could not be influenced by nor could observe the decisions of any of the other participants at any time. The experiment was completely computerized except that subjects were provided with two sheets of paper: a *Production Schedule* and a *Token Value Sheet*. The Production Schedule described the production function and the Token Value Sheet described the utility function. Both sheets can be found in the appendix that follows this paper, along with the full text of the computerized instructions.

There are three variables described in the Production Schedule. The first variable is the current level of capital stock k_t labelled as *Units of A Used in Production*. If the agent uses all of his capital for production at time t, this provides $f(k_t) + .5k_t$ to divide between consumption for the current round c_t and capital for the next round k_{t+1}. The term $.5k_t$ is the undepreciated capital stock in round $t+1$. The amount $f(k_t) + .5k_t$ is indicated by *Total A + X Produced* on the Production Schedule. If the subject consumes the maximum amount possible, his remaining capital stock equals $.5k_t$, the amount that results by allowing the capital stock in k_t to depreciate and making zero gross investment in the round. This amount ($.5k_t$) is given in the column entitled *Minimum A*. If the subject consumes zero in round t, his capital stock in round $t+1$ is $k_{t+1} = f(k_t) + .5k_t$.

In each round t each subject chose a level of capital stock $k_{t+1} \in [.5k_t, f(k_t) + .5k_t]$. Before committing himself to a specific choice, a subject could type in any value for k_{t+1} and the

[5]There have been several other experimental studies focused on dynamic individual choice problems. The evidence is mixed on whether subjects are successful in solving problems of this type. For example Fehr and Zych (1996) study a dynamic decision problem in which subjects are given incentives to intertemporally optimize the consumption of a fictitious addictive good. Consumption at any point in time lowers the marginal utility of consumption in future rounds, similarily to the building up of a tolerance to an addictive substance. They find a tendency toward excess consumption. Noussair and Olson (1997) study decisions over a ten round horizon in a setting in which at most twelve discrete choices were available in each round. They find that decisions are generally suboptimal at first, but improving with repetition, with some tendency toward overdepletion of capital stock near the end of the time horizon. Cox and Oaxaca (1992) study behavior in search experiments and find early termination of search compared to the optimal decision of a risk-neutral agent but consistent with a theoretical model postulating risk aversion. An interesting experimental literature has concerned the study of dynamic decision making with a focus on how agents discount the future. See for example Albrecht and Weber (1997), Benzion, Rapoport, and Yagil (1989), Gigliotti and Sopher (1997), Loewenstein (1987, 1988) and Thaler (1981). These studies have tended to find strong departures from standard theoretical models of intertemporal choice.

computer calculated the implied value of c_t (given by (2) when (2) holds with equality) as well as $u(c_t)$. Consumption good was consumed immediately and could not be stored for future rounds. Of course, however, undepreciated capital stock did carry over to future rounds. The entire past history of the individual's *own* choices was accessible on the computer screen at all times to help in making decisions.

Subjects were awarded $u(c_t)$ tokens in each round, based on how much c_t they produced, according to (14). $u(c_t)$ was expressed in terms of tokens earned for producing units of c_t in a round and was indicated to each subject on his *Token Value Sheet.* The same utility function was used each round. In each round the tokens received were added to the total earned. The tokens earned could be converted to US dollars or Japanese Yen at the end of the experimental sessions at a rate known in advance to subjects. Thus, maximizing cash earnings in a period of the experiment were equivalent to maximizing (1) and subjects' cash earnings in a period were proportional to the value of (1) attained. The first three periods did not count toward subjects' earnings. The next twenty periods did count toward final earnings. There were no participation fees or other non-salient rewards given in the experiment.

Subjects were required to spend at least 75 minutes on the instructions and making decisions in the 23 periods. They were informed that they would not be able to receive their actual cash payments until the 75 minutes had elapsed. They were not allowed to engage in any activity other than the experiment during the 75 minutes. These requirements were intended to reduce the incentive to make decisions as quickly as possible. Earnings varied between $9 to $20 in the American sessions and between 900 and 1800 Yen (1 $US = 125 Yen) in the Japanese session.

3.3 Random Versus Fixed Ending

In the basic design, the infinite time horizon was implemented by using a probabilistic ending rule, which we call the *Random Ending* rule. The use of a probabilistic ending rule to represent an infinite horizon model yields the same optimal solution as the deterministic infinite horizon model only under the assumption of risk neutrality in the final monetary payoff on the part of subjects. To see this, let m_i^j equal the money a subject earns in period j. and $E(m_i^j)$ the expected earnings of subject i in period j.

$$E(m_i^j) = \sum_{t=0}^{\infty} p_t u(c_t) \tag{15}$$

where p_t is the probability that the period continues until at least round t. If p_t is chosen so that

$$p_t = (\frac{1}{1+\rho})^t \tag{16}$$

then equation (15) is the same as the maximand in equation (1). The correct p_t can be induced by specifying a probability $\frac{\rho}{1+\rho}$ of the period ending after the current round. Let $V_i(\sum_{j=1}^{20} m_i^j)$ be the subject's utility for the final monetary payoff in the experimental session, which has 20 periods with monetary payoffs. If the agent is risk neutral in the final monetary payoff, then choosing c_t to maximize the expected value of (15), a problem with exogenous uncertainty, is equivalent to (1), a problem with no uncertainty. However, if the agent is risk-averse, the two problems are no longer equivalent. Risk aversion affects the optimal solution in maximizing (15), in which uncertainty is present, but does not affect the maximization of (1) in which there is no uncertainty. Under the Random Ending rule, risk aversion would lead the agent to consume a greater fraction of her resources than under risk-neutrality, in order to smooth out payoffs for differing realizations of period length, even if it involves a lower expected monetary payment for the period.

Thus, if a lower than predicted level of investment were observed in the basic design, one possible explanation would be the presence of risk aversion. We therefore added the *Fixed Ending Rule* treatment in which there was no uncertainty about the final round of the period. Under the Fixed Ending Rule, each period consisted of ten rounds. In addition to receiving tokens based on their consumption in each round, subjects earned tokens based on the level of capital stock they held after round 10.[6] In order to make the optimal solution exactly the same as in the Random Ending treatment, the number of tokens awarded for terminal capital stock was the (discounted) quantity of tokens which they would receive if they were to make the optimal decisions beginning in round 11 over an infinite horizon.

Because the period had zero probability of ending before round 10 under the Fixed Ending Rule, and in order to make the decision problem identical under the two ending rules, the payoffs from consumption in rounds 1-10 were discounted by 10 percent from round to round. Instead of an identical token value sheet in each round, as in the Random Ending treatments, subjects received ten different sheets, one for each round, which reflected the discounting that occurred round by round. There was also a Token Value Sheet for A, which indicated the final buyout values of capital stock after round 10. Any given subject used the same eleven sheets in every period. The Fixed Ending Rule was only used for the Slow/Low parameters. This choice was made because initial experimentation with the Random Ending Rule indicated an underinvestment in capital stock under Slow/Low, and we conjectured that risk aversion in the final monetary payoff might have been the cause.

3.4 Cross-Cultural Differences

We had an opportunity to test the robustness of our results with a second subject pool, undergradutes at Waseda University in Tokyo, Japan. The use of Japanese subjects is of particular interest in light of the different patterns of saving and consumption between residents of Japan and of the United States. In the session run at Waseda, the .9 (Slow) production function was used. Of the eleven subjects from Waseda, six had an initial endowment of 3 (Low) and five

[6] Though the infinite horizon in the theoretical model in section two is stated as beginning in round zero, in the experimental sessions the initial round was presented to subjects as round 1, because we thought the label of round 0 might suggest to subjects that the round was a practice round that did not count toward their earnings. In sections 3-6 we will refer to the initial round in a period as round 1, as we did in the experiment.

had an initial endowment of 50 (High).

3.5 Data Available

Table 2 below summarizes the available data, by initial endowment, production function, ending rule and location.

[Table 2: About Here]

The basic design consisted of the four treatment cells, Slow/Low, Slow/High, Fast/Low and Fast/High. All of the data in the basic design used the Purdue subject pool and the Random Ending Rule. The basic design therefore allows for comparisons between the two levels of initial endowment and the two production functions.

4 Hypotheses

The eight hypotheses listed in this section are, with the exception of hypothesis eight, implications of the theoretical model outlined in section 2. The optimal sequences of capital and consumption in all four cells of the basic design are given in table 3. Since the steady state capital stocks ($\bar{k}$) are equal in the 4 cases, comparisons of speed of convergence are easy. Increases in the capital parameter α slow convergence to the steady state both in absolute value and in proportional terms. Convergence to the steady state is monotonic, and at a decreasing rate in absolute value. Capital and consumption are to the same side of their steady state values. [7]

[Table 3: About Here]

[7] The last result is apparent from the phase diagram in Figure 1, because the stable manifold S is monotonically increasing in k. The model has other comparative statics and dynamics predictions, which are not directly examined in the experiments reported here. In particular, increases in discounting (ρ) and depreciation (δ) produce faster convergence, and changes in ϕ have no bearing on speed of convergence in proportional terms. King and Rebelo [1993] demonstrate that changes in substitution rates, between factor inputs, and between consumptions at different dates, can affect transition paths.

The first hypothesis is derived directly from the data in Table 3. We do not expect the exact point predictions of the theoretical model to be observed, because we recognize that the required calculations are very demanding for subjects. However, we do hypothesize that there is no systematic tendency for capital stocks to be higher or lower than those along the optimal trajectory.

Hypothesis 1 *Median capital stock holdings are no different than along the optimal trajectory.*

Hypothesis 1 postulates that there is no general bias toward over-or underconsumption. The second hypothesis concerns a more general implication of the theoretical model, which makes clear predictions about increases and decreases over time in capital stock levels. We state hypothesis two in both a strong and in a weak version. The strong version, which is a restatement of Property 2 of Section 2.2, says that when initial endowment is Low (High), subjects should increase (decrease) capital stock holdings monotonically over the course of a period, but not overshoot the optimal steady state level of capital stock. The weak version of the hypothesis takes into account the difficulty of determining the optimal steady state level of capital stock and therefore merely requires monotonicity of the capital stock holdings.

Hypothesis 2 *Strong Version:* $\bar{k} > k_{t+1}^{L} > k_{t}^{L}, \forall t$ *and* $\bar{k} < k_{t+1}^{H} < k_{t}^{H}, \forall t$. *Capital Stock Holdings are Moving Monotonically Over Time Toward the Optimal Steady State Level.*
Weak Version: $k_{t+1}^{L} > k_{t}^{L}, \forall t$ *and* $k_{t+1}^{H} < k_{t}^{H}, \forall t$ *Capital Stock Holdings are Moving Monotonically Over Time but Possibly Overshoot the Optimal Steady State Level.*

While hypothesis two is concerned with the direction of convergence, hypothesis three deals with the speed of convergence, and is also stated in a strong as well as a weak version.

Hypothesis 3 *Strong Version: For all t,* $|k_t^F - \overline{k}| < |k_t^S - \overline{k}|$ *and the strong version of Hypothesis 2 holds. The Speed of Convergence to the Optimum is Greater in the Fast Treatments than in the Slow Treatments.*

Weak Version: For all t, $|k_t^F - \overline{k}| < |k_t^S - \overline{k}|$. *Capital Stock Holdings are Closer to the Optimal Steady State Level in the Fast Treatments than in the Slow Treatments.*

Both versions of Hypothesis 3 are versions of Property 4 of Section 2.2. The strong version requires that convergence of the capital stock toward the optimal steady state level take place and that the speed of convergence take place more quickly in Fast treatments than in Slow treatments, given the same initial endowment. The weaker version merely states that, controlling for t, the capital stock in the Fast convergence treatments should be closer to the optimal steady state level than in the Slow convergence treatments. Both the strong and the weak version can be evaluated in the High and Low endowment data separately. Hypotheses 4-6 are statements about differences between decisions and earnings in different treatments, and are all implcations of the theoretical model, which predicts a failure to reject all three null hypotheses.

Hypothesis 4 *There are no differences in the earnings realized, relative to the maximum possible earnings between the four treatment cells of the basic design.*

Hypothesis 5 *There are no differences in decisions and earnings realized, relative to the maximum possible earnings between the American and the Japanese subjects.*

Hypothesis 6 *There are no differences in decisions between the Fixed Ending Rule and the Random Ending Rule.*

Hypothesis four asserts that subjects can solve all of the problems in the basic design equally well. The theoretical model predicts that decisions follow the optimal path in all treatments and therefore that there would be no difference in earnings across treatments relative to the optimum. All of the subjects in the basic design are drawn from the same subject pool and use the same ending rule so that any differences in earnings would be due to some aspect of the actual parameters of the decision problems which might create a tendency to make more costly errors in decision making in some of the treatments relative to others.

Hypotheses five and six are methodological diagnostics which, if supported, could strengthen the results obtained from the data from the basic design. Hypothesis five asserts that the decisions of subjects do not differ between the two subject pools. Both groups of subjects were undergraduates at large universities, with no previous experience in economic experiments. If subjects at both universities generate similar patterns in the data, we would interpret this as support for our main results, especially considering the cultural differences between the two groups.

Hypothesis six postulates that subjects' risk aversion in the final monetary payoff is not strong enough to induce significantly different behavior under the two different ending rules. The hypothesis also rules out other causes of any differences in decisions under the two ending rules, and supporting the hypothesis would indicate that decisions do not depend on the manner in which we induced the payoff structure of the infinite horizon.[8] Hypothesis seven considers behavior in the final round of periods using the fixed ending rule, the only situation in the study when the period ends with probability one immediately after the current decision.

Hypothesis 7 *Strong version: Optimal decisions, conditional on current capital stock holdings, are made in round 10 under the Fixed Ending Rule.*
Weak version: $|k_{10} - \bar{k}| < |k_{11} - \bar{k}|$.

This is the easiest decision situation in all of the treatments. There is no uncertainty and there are no dynamic considerations, because the period ends with certainty after the current round. The strong version states that subjects take the optimal decision, given the capital stock in round 10. The weak version is that the capital stock is moving in the correct direction in round 11 relative to round 10. Hypothesis eight, unlike the previous seven hypotheses, is not an implication of the theoretical model, but rather is suggested by previous experimental studies.

[8]The hypothesis covers only decisions and not earnings because comparisons of earnings between the two ending rules are difficult. Under the Fixed Ending Rule, the terminal value of capital stock awarded to subjects assumes that optimal decisions would be made after round 10.

Hypothesis 8 *The earnings of subjects relative to the optimum are greater in the later periods of a session than in the earlier periods.*

Hypothesis eight is a well-documented pattern in experimental economics. The performance of subjects, as measured by their cash earnings, tends to improve as they repeat the decision situation. Because of this effect, much of the analysis that follows focuses on behavior in the later periods of the sessions.

5 Results

5.1 Overview of Patterns in the Data

5.1.1 Capital Stock Holdings

Figures 2a-8b show the level of capital stock holdings in period 5, the second period that counted toward subjects' earnings, in each of the seven treatments as well as the data from period 19 in all seven treatments. Each of these two periods lasted 15 rounds under the Random Ending Rule.

[Figures 2a-8b: About Here]

Figures 2a and 2b show the data for the Slow/Low treatment for periods 5 and 19 respectively. The final level of capital stock was less than the optimal level for all of the subjects in period 5 and for all but one of the subjects in period 19. In period 5, no subject is monotonically increasing capital stock holding over time and seven of the eleven subjects are monotonically decreasing their holdings, which contrasts sharply with the theoretical prediction of monotone increase. In period 19, the problem persists as no subject monotonically increases his capital stock, but five of the eleven subjects monotonically decrease it. It is apparent from the figures that there is a tendency to underinvest in the Slow/Low treatment.

In Figures 2a and 2b we also observe several occurrences of a phenomenon we refer to here as a "binge". We will say that a subject *binges* if he consumes the maximum possible amount in a round, that is, he sets $k_{t+1} = .5k_t$. In the period 5 data, one of the subjects binges in every round, and ten of the eleven subjects binge at least once in period 5. In period 19, we also observe at least one binge on the part of six of the eleven subjects.

Figures 3a and 3b show the data from periods 5 and 19 of the Slow/High treatment, in which the initial endowment was 50 and the .9 production function was used. As theory predicts, many subjects tend to monotonically reduce their level of capital stock over the course of the period. However, the reduction in capital stock is usually quicker than is optimal. At the end of period 5, nine of the ten subjects have less than the predicted capital stock holding and at the end of period 19, eight of ten do. Frequent binging is observed. On the whole there is underinvestment in this treatment.

In Figure 4a, which displays data from Fast/Low, with an endowment of 3 and the .2 production function, there is frequent binging on the part of subjects in period 5. Each of the ten subjects binges in at least one round during the period. Unlike in the Slow/Low and Slow/High treatments, the binging in Fast/Low is often preceded by a large investment in capital. By period 19, as shown in Figure 4b, there is substantially less binging, though seven out of ten subjects binge at least once. As can be seen in Figure 4b, by period 19, seven of the ten subjects possess a quantity of capital stock greater than the optimal level.

Figures 5a and 5b correspond to treatment Fast/High, in which the endowment of capital stock was 50 and the .2 production function was in effect. In the early period, there is a lot of binging, and the majority (8 of 11) subjects deplete their capital stock down to a level below their optimal steady-state level in round 15. By period 19, however, the subjects are investing more, and the capital stock of six of the eleven subjects exceeds the level along the optimal trajectory.

Figures 6a and 6b show the data from the Slow/Low/Fixed treatment. There is widespread monotonicity, though usually in the opposite direction as predicted. In period 5, eight of the twelve of the subjects are monotonic, and seven of the eight are monotonically decreasing their capital stock, whereas the theoretical prediction is monotone increase. For two of the subjects a binge is observed. In the late period, four subjects are monotonically increasing, four are monotonically decreasing, one subject is keeping a constant level of capital stock, and three are not monotonic. One subject binges in the last two rounds. The incidence of binging is somewhat lower under the Fixed Ending Rule than under the Random Ending Rule.

The data from Slow/Low/Waseda are displayed in Figures 7a and 7b. In period 5, four of the six subjects monotonically decrease their capital stock. One subject builds up to a capital stock of 17 and subsequently binges, so that by the end of the period, all subjects have less than the optimal level of capital. In period 19, three subjects are monotonic decreasers, and all subjects have a capital stock below the optimal level in round 15.

The Slow/High/Waseda data are in Figures 8a and 8b. In both the early and the late period, all subjects monotonically decrease, and with the exception of one of the subjects in period 19, all decrease capital stock faster than is optimal.

5.1.2 Consumption Patterns

[Figures 9-15: About Here]

Figures 9-15 illustrate the consumption by round during period 19 for all seven treatment cells. Figure 9 shows the consumption patterns in the Slow/Low treatment. In the early rounds of the period there is overconsumption. In round 1, ten of the eleven subjects consume more than the optimal quantity. By the end of the period, most of the subjects are consuming less than along the optimal trajectory, a consequence of their earlier overconsumption and depletion of capital stock. Consumption binges can be seen as "spikes" on the graph.

A similar pattern is evident in Figure 10, which shows the consumption by round in period 19 under Slow/High. Ten of eleven have too little capital stock by round 15. As in Slow/Low, consumption by round is not nearly as smooth and regular as the theoretical prediction. Instead, frequent binging is observed.

In Figures 11 and 12, which graph the data from the Fast treatments, underconsumption is usually observed in the early periods, but consumption is on average close to the theoretical prediction of 35.78 in later rounds in both treatments, though some subjects exhibit an oscillating pattern of consumption behavior. In these two treatments, unlike in the Slow treatments, some of the subjects (3 subjects in Fast/Low, and 4 subjects in Fast/High) consume nearly constant amounts which are very close to the optimal steady state level. Most of the subjects who oscillate between high and low consumption have an average consumption close to the optimal level.

Figure 13 graphs consumption decisions in Slow/Low/Fixed. As in the Slow/Low and Slow/High treatments, most of the subjects (10 out of 12) consume more than the optimal amount in the early rounds and, because they excessively deplete their capital stock, 9 of 12 consume less than the optimum in the late rounds.

Figures 14 and 15 contain the data from the Waseda treatments. In the Slow/Low/Waseda treatment, the data in figure 14 indicate overconsumption in early rounds followed by underconsumption in later rounds. In Figure 15, in which the Slow/High/Waseda data is graphed, the data show that the consumption of four of the five subjects closely tracked the optimal trajectory in the later rounds, while one subject binged in every round. In round 1, four of the five subjects consumed more than the optimal amount.

5.1.3 General Patterns in the Data

An overall picture emerges from figures 2a-8b. Under the Fast production function, there is great variation across indivduals, but by period 19, a majority hold more capital stock than along the optimal path. Average consumption is close to the optimal steady state level, though with considerable variation round by round. Under the Slow production function, however, there is a strong general tendency to underinvest, regardless of initial endowment, subject pool, or ending rule. Under the Slow production function, consumption is greater than the optimum in the early rounds of a period, but since capital stock is depleted during the course of the period, the consumption in late rounds is lower than along the optimal trajectory. In all of the treatments, there is a tendency to binge and it is often the case that the same subject binges more than once a period. The next subsection details the results of statistical tests of the hypotheses listed in section 4.

5.2 Tests of Hypotheses

In this section we discuss the degree to which the data support the hypotheses listed in Section four. Results 1-8 address hypotheses 1-8, in order. The first result considers deviations in capital stock from the theoretical prediction, confirming the observations of section 5.1.

Result 1: Whether overinvestment or underinvestment relative to the optimum occurs depends on the production technology. Under Slow, there is underinvestment and under Fast, there is overinvestment.

Support for Result 1: Table 4 compares the end-of-period capital stock holdings to the predicted level for all seven treatments, in the last five periods, for all subjects.[9] In all of the Slow treatment cells, the majority of end of period capital stock holdings are lower than the optimal level. As can be seen in the last column of table 4, we can reject the hypothesis that the capital stock holdings are equally likely to be greater than or less than the predicted value at the

[9] We use the last five periods in evaluating hypotheses 1-3, because decisions taken during these periods can be based on experience with previous periods of different lengths, which allows subjects to understand the rule for ending each period. The lengths of the last five periods were 15, 4, 2, 8, and 7 rounds. In table 4 there are five observations for each subject, one for each of the last five periods.

$p < .05$ level of significance for Slow/Low, Slow/High, Slow/Low/Fixed, and Slow/Low/Waseda. In both of the Fast treatment cells the majority of capital stock levels are higher than the optimal level. For Fast/High we can reject the hypothesis that the holdings are equally likely to be higher or lower than the optimal value at the $p < .05$ level.[10] The same impressions are obtained from figures 2a-8b. □

[Table 4: About Here]

The next result documents the widespread nature of the monotonicity of capital stock in the data. The result also shows, however, that the monotonicity is not always consistent with the theoretical prediction. Under Slow/High and Slow/High/Waseda, the monotonic sequences are often observed to overshoot the optimal steady state level of capital stock and, in the Slow/Low, Slow/Low/Fixed and Slow/Low Waseda treatments, to usually move in the opposite direction as predicted.

Result 2: Most observed sequences of capital stock are monotonic, as predicted. However, under Slow/High capital stock is depleted too quickly, and under Slow/Low, capital stock is usually monotonically decreasing, contrary to the theoretical prediction of monotonic increase.

Support for Result 2: Table 5 lists the number of instances of monotonically increasing capital stock, monotonically decreasing capital stock, and binging, for each treatment cell. Each observation represents one entire period and for an observation to be classified as a monotonic increase (decrease) the subject must increase (decrease) capital stock holdings in every round of the period. The table contains all of the data from the last five periods for all subjects.

[10]Consider the variable x_i where $x_i = 1$ if the end of period capital stock is greater than the optimal steady state level and $x_i = 0$ if it is less than the optimal steady state level. We evaluate the hypothesis that x_i is drawn from a distribution with $P(x_i = 1) = P(x_i = 0) = .5$.

[Table 5: About Here]

Under both of the High Endowment treatments the large majority of subjects, in both subject pools and for both production functions, are monotonically reducing their capital stock in each round, as predicted. However, as can be seen in Figures 3, 5 and 8, this reduction in capital stock frequently goes beyond the optimal level of 14, especially for the Slow production function. In the Slow/Low treatments, 56 percent of the Purdue subjects and 43 percent of the Waseda subjects are monotonically decreasing their capital stock holdings, which is counter to the prediction, whereas only 25 percent of the Purdue subjects and 17 of the Waseda subjects are monotonically increasing, as predicted. Under the Fixed Ending rule and Low Endowment, 40 percent are monotonically decreasing and 20 percent are monotonically increasing. Thus, under the Slow production function and Low Endowment, regardless of subject pool and ending rule, *about twice as many subjects are monotonic in the wrong direction as in the correct direction.* Under Fast/Low only 18 percent of the subjects choose a monotonic sequence of capital stock holdings, a far lower percentage than in any other treatment cell, though most sequences are in the predicted direction. Thus, the strong version of Hypothesis two is not supported, neither under High nor under Low Endowment and the weak version of Hypothesis two is supported for High Endowment only. □.

The next result evaluates hypothesis three, which concerns the speed of convergence.

Result 3: The theoretical predictions regarding differences in speed of convergence between treatments are not supported.

Support for Result 3: The proposition is evaluated for the last five periods of data from the basic design. The strong version of hypothesis three is not supported because the strong version of hypothesis two is not supported. As for the weak version of hypothesis three, in each of the last five periods, the average end-of-period deviation from 14 is greater under Fast/Low than under Slow/Low, the opposite of the theoretical prediction[11]. The average end-of-period deviation is greater under Fast/High than under Slow/High in two of the five periods. □

The next result focuses on the costliness of the departures from the optimal trajectory documented in Results 1-3, by comparing observed earnings to earnings along the optimal decision path. We use a measure called *efficiency*, a widely used measure of welfare in experimental economics, to compare earnings in different treatments.

Define the *efficiency* of subject i's decision in period j, E_i^j, as:

$$E_i^j = \text{(Earnings obtained by subject)/(Earnings along optimal path)}$$

where earnings refer to monetary payments, which are proportional to the realized value of the maximand in (1). Thus, efficiency represents the percentage of the payoff actually realized by the subject compared to the payoff he would have received by following the optimal policy.[12] As suggested by the earlier results, we can identify differences in earnings in the different treatments. The differences are described in the statement of result 4.

Result 4: Observed efficiency of decisions differs between treatments of the basic design. Efficiency is greater under the Fast than under the Slow production function. Efficiency is greater when the initial endowment is High than when it is Low.

[11]For each of the last five periods we calculate the average (across subjects) deviation in capital stock from the optimal level after the last round for each treatment (five different averages for each treatment, one for each of the last five periods). We then perform a pairwise comparison of the averages between Slow/Low and Fast/Low as well as between Slow/High and Fast/High.

[12]Note that when the Random Ending Rule is in effect, the earnings resulting from decisions along the optimal path are optimal in expectation given the distribution of period lengths, but are likely to be suboptimal for the actual realization of period lengths (an agent could improve earnings by consuming as much as possible immediately before the period ends). Therefore it is possible for efficiency to take on values greater than one. Of course, under the Random Ending Rule, the subject is unaware of when the period will end at the time he makes his decisions.

Support for Result 4: Table 6 shows the results of an Error Component Estimation of efficiency. The coefficient of the variable *Slow/Low* indicates the average efficiency for the Slow/Low treatment, 71.3 percent. The variable *High* takes on a value of 1 for the High Endowment treatment and 0 for Low Endowment. The variable *Fast* takes on a value of 1 for the Fast treatment and 0 for the Slow treatment. The variable *Fast/High* is an interaction term between Fast and High. The variable *Fixed* equals 1 in the Fixed Ending Rule is in effect and 0 otherwise. *Waseda* equals 1 if the data are generated by a Waseda University subject and 0 otherwise. Each unit of observation in the data described in table 6 is the overall efficiency attained by one subject for the entire session so that there were a total of 65 observations. The actual average efficiencies are given in the last column of table 7. The effect of the High endowment and Fast production function are both positive and significant at the 5 percent level, and the interaction term between High and Fast is not significantly different from zero. The actual average efficiencies in each treatment can be found in the last column of table 7. □

[Table 6: About Here]

The data in Table 6 allow us to address Hypothesis 5 and to state Result 5.

Result 5: There is a significant subject pool difference. The Waseda subjects receive higher earnings than the Purdue subjects.

Support for Result 5: The earnings result is seen from the data in Table 6. The coefficient for Waseda is positive and significant at the 5 percent level. □

The Waseda subjects appear on average to be more sophisticated decision makers than the Purdue subjects. However, they are subject to the same types of bias. Under both the Slow/Low and the Slow/High parameters, both groups underinvest and overconsume, as can be seen in the figures in section 5.1.

Result 6: Holdings of capital stock in the Slow/Low treatment are not different under the Fixed Ending rule than under the Random Ending Rule.

Support for Result 6: Comparing capital stock holdings in round 10 of the Slow/Low and Slow/Low/Fixed treatments in the last five periods using a rank-sum test, we find no significant difference at the five percent level of significance. The capital stock is lower than the optimal level under the Fixed Ending Rule, as it is under the Random Ending Rule (see Table 4). □

Result 6 is important because it indicates that the tendency to overconsume in the Slow/Low treatment is not a consequence of the Random Ending Rule. Result 7 considers what is in principle the easiest decision situation in all of the treatments, that in round 10 under the Fixed Ending Rule.

Result 7: Decisions are not optimal in round 10 in the Fixed Ending Rule treatment. Capital stock holdings are moving toward the optimal steady state from rounds 10 to 11 in only 1/3 of the observations.

Support for Result 7: Overall, capital stock is moving in the correct direction over time in 80 in 240 observations. In period 22, the final period, when subjects have the most experience, capital stock moves in the correct direction for 5 of the 12 subjects. □

In S/L/F, as in S/L and S/L/W, the capital stock tends not to move in the correct direction over time. However, considering the variable $z = (k_{11} - k_{10}) * (k_{10} - k_9)$. A value of $z > 0$ means that capital stock is moving in the same direction from round 10 to 11 as it did from round 9 to 10. In the data from the last five periods under the Fixed Ending Rule, $z > 0$ in 49 out of 60 observations, while $z = 0$ and $z < 0$ for 10 and 1 observations respectively. This indicates that capital stock movements between round 10 and 11 are usually part of a strategy of reducing or increasing capital stock over two or more rounds. The next result considers changes in earnings over the course of the session.

Result 8: Decisions are improving over time in some, but not all of the treatments.

Support for Result 8: Consider the following regression equation:

$$E_i^j = \beta_0 + \beta_1 Period + \beta_2 Rounds \tag{17}$$

Where E_i^j = observed efficiency, Period = period number (the first period that counts toward earnings is coded as period 1 in the estimation, though it was actually the fourth period in the experiment, because it was preceded by three practice periods), and Rounds = number of rounds in the period. The equation is estimated for each treatment separately. The results are given in table 7.

[Table 7: About Here]

The results are mixed. The effect of the variable Period, is significantly positive for Fast/High and Slow/Low/Fixed but insignificant for the other treatments. □

Table 7 also shows the effect of the period length on earnings relative to the optimum. The coefficient of *rounds* is negative for all four of the Slow treatments, Slow/Low, Slow/High, Slow/Low/Waseda, and Slow/High/Waseda. The intercept is greater than 1 for the Slow/Low and Slow/Low/Waseda treatments.[13] This is further evidence of overconsumption in Slow/Low, which raises earnings in short rounds and lowers earnings in longer rounds. In periods in which the period ended after a short number of rounds, earnings were on average higher than the theoretical prediction. In Fast/Low, in which there was overinvestment, efficiency was greater

[13] Though the payoff is greater than along the optimal trajectory in Slow/Low for periods consisting of relatively few rounds, it is less than along the optimal trajectory during longer periods. This leads to lower average earnings because longer periods have greater weight in final earnings and in the average earnings calculations in table 7.

in longer periods.

6 Discussion

The question of whether agents underinvest or overinvest relative to their optimal policy is a question without a straightforward yes or no answer. Rather, the answer depends on the parameters of the particular economy of interest. In the economies studied here, we are able to identify an economy in which underinvestment consistently occurs as well as an economy in which there is overinvestment on average, and whether or not underinvestment or overinvestment takes place depends on the production technology available in the economy. The Fast production function leads to moderate overinvestment while the Slow production function leads to costly underinvestment.

Sudden episodes called binges, in which a subject consumes as much as possible in a given round, were widely observed in all of the treatments. Smoothing out consumption over time seems to be a difficult concept for subjects. The binging persists even after many repetitions in the same decision situation. The binging does not appear to be a manifestation of confusion or random behavior, but rather it seems that many subjects have decided that their best strategy is to suddenly consume as much as possible (often after building up capital stock) in the apparent belief that the optimal decision is to concentrate consumption in one or a few rounds rather than smoothing it out over all rounds.

At first glance, a plausible explanation for binges, under the Random Ending Rule, is that subjects consume as much as possible in anticipation of the end of a period (rather like an investor attempting to "time the market" when making changes to one's stock portfolio). A correctly timed binge can raise ex-post earnings. In fact, the incidence of binges is about 25% lower under the Fixed Ending Rule than under the Random Ending Rule. However, 75% of the binges cannot be accounted for by the ending rule. More generally, behavior did not differ substantially between Slow/Low and Slow/Low/Fixed. There was overconsumption in both treatments. Thus, we have no evidence that the two ways of representing the infinite horizon generated behavior substantively different from each other. Of course, we do not know (and we may never know) whether behavior in an actual infinite horizon would be different from under our ending rules.

Decisions are better, in the sense that they lead to higher values of the objective function under the Fast than under the Slow production function. Under the Fast production function, the marginal product of capital is more elastic, which means that if the capital stock gets lower than the optimal level, it can be quickly increased at low opportunity cost, and if it gets higher than the optimal level, the marginal product decreases rapidly, making further positive net investment more and more costly as capital stock increases. These properties tend to keep consumption at close to the optimal level. The adverse impact of binging is more severe in the Slow than in the Fast treatments, because it is more costly to rebuild capital stock under Slow than under Fast.

Decisions are better under High Endowment than under Low Endowment. Under High Endowment, in which it is optimal to reduce capital stock holdings over time, binges tend not to be as costly as they are under Low Endowment. The most difficult decision problem was Slow/Low, in which instead of monotonically increasing capital stock holdings over time, as predicted, subjects tended to monotonically *decrease* them. This behavior is not due to risk aversion, nor to an incorrect assessment of the probability of the period ending, since it also occurs under the Fixed Ending Rule.

Our results are strengthened by the use of two subject pools, Japanese as well as American subjects, and the observation of similar data in the two groups. Though the Japanese subjects received higher earnings than the American subjects, they exhibited the same type of departures from the theoretical prediction. Under the Slow production function, underinvestment is observed by the members of both subject pools. Binges are also observed among the Japanese subjects though they are less common than among the American subjects.

In round 10 under the Fixed Ending Rule, a majority of subjects are changing their capital stock in the incorrect direction. This particular problem is a one stage problem, because with certainty there are no future rounds. Subjects did not equate the marginal utilities of the consumption and investment goods. The decision in the final round seems to be affected by the context in which it is played, as a subgame in a larger game. Subjects adopted policies of either increasing or decreasing capital stock over the entire horizon of the period, and decisions in the last round reflect a continuation of the policies of earlier rounds.

The conditions under which precise theoretical predictions can be observed do not include the setting of our experiment. However, we do not interpret the results here as grounds to "reject" the behavioral relevance of the theoretical model under all circumstances. We recognize that the decision problems studied here are complex. More training, the correct type of experience, or perhaps a different user interface is required to successfully solve problems of this type. However, it does appear that, for subjects to correctly solve dynamic optimization problems, there exist strong biases which must be overcome.

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A Instructions and Sheets

This appendix contains the complete text of the computerized instructions of the experiment, as well as a *Production Schedule* and a *Token Value Sheet*.

Instructions for Experiment

This experiment is part of a study of decision making. Various research foundations have provided funds for this research. The instructions are simple and, if you follow the instructions carefully you can generally expect to make a substantial amount of money, which will be paid to you IN CASH at the end of the experiment.

One important rule of this experiment is that once we begin, no one is allowed to talk or communicate in anyway to anyone else. Anyone that does talk or communicate to someone else will lose their right to payment.

I. What determines how much you will be paid?

A. The amount of your payment depends partly on your decisions and partly on chance.

B. The payoffs in the experiment are not necessarily fair, and we cannot guarantee that you will earn any specified amount.

C. However, if you are careful you can generally expect to make a substantial amount of money.

D. During the experiment payoffs will be given in "tokens" or "points". You are awarded tokens by producing X during the course of the experiment. The tokens will be exchanged for dollars at the end of the experiment. Each 700 tokens are worth 1 dollar.

II. How does the experiment work?

A. The experiment consists of a series of games.

B. Each game will consist of a certain number of rounds, and the number of rounds in a game will vary from game to game. In each round you will make decisions about how much of two goods, A and X, to produce.

C. At the start of each game you will be given 3 units of good A.

D. You will then be asked to make A and X by choosing quantities from the Production Schedule, one of the sheets of paper given to you.

E. You will then be awarded a fixed number of tokens based on how much X that you produce. You can see how many tokens you get for the X you make on the sheet entitled 'Token Value for X'. You can receive tokens in every round. The way that you read and use the Token Value for X sheet will be explained to you shortly. In each round the tokens that you receive are added to your total.

F. The X that you produce DOES NOT carry over to the next round. However, the A that you produce DOES carry over to the next round. You need to produce A in the current round in order to be able to produce X in subsequent rounds.

G. Notice that if you make too much X and too little A in the early rounds, you may not have enough A remaining to make as much X as you would like in the later rounds.

H. There will be 3 practice games; after which will be the 20 games played for money.

I. After the last game you will be paid in dollars at the rate of 700 tokens to 1 dollar.

III. How many rounds are there in a game?

A. In any given round, there is a 10 percent chance, that is, the odds are 1 in 10, that the game ends right after the current round. There is always a 90 percent chance that there will be at least one more round in the current game.

B. This means that in any given round, there will be on average 10 more rounds in the current game.

C. Some games may be much longer than other games.

D. The number of rounds in a game is not affected by the number of rounds in previous games. In other words, if one game happens to be long, it does not necessarily mean that the next game will be short or long.

Before we begin some practice games the INPUT SCREEN will be explained.

The INPUT SCREEN allows you to input your choice. It also - Shows you the current game. - Shows you the choices of A and X you have made. - Allows you to see outcomes of all past games.

It is divided into 2 parts:

The HISTORY Window: - Shows the outcome of the last game and all past games by pressing the PageUp and PageDown keys.

The INPUT Window:

To input your choice move the cursor to the Input A or Input X position by using the left and right arrow keys. Then type in your choice and press ¡enter¿. After you enter your choices for both A and X you can complete your choice by pressing the F10 key; you will be asked to confirm it by pressing the Y (for YES that is the right choice) or by pressing the N (for NO that is not the right choice). Pressing the N key will allow you to change your choice.

You have two sheets in front of you: the Production Schedule and the Token Value Sheet for X.

Please Refer to the Production Schedule:

A. This sheet indicates the amount of X and A which you can make from a given amount of A in each round. The same sheet is to be used in every round of every game.

B. The first column indicates the amount of A you currently have.

C. The second column shows the total quantity of A + X that you can produce this round with the amount of A you currently have. For example, if you have 10 units of A this round, you can make a total of 12.02 units of A and X this round.

D. On the table, the values are given only for integer values of A, but if you have a quantity of A that is not an integer, say 23.4, you can still produce more than if you had 23. You can see how much A+X you can produce in the field labelled TOTAL A+X on your screen.

E. However, in each round, you are required to produce at least the amount of A given in column 3, entitled MINIMUM A, during each round. This minimum amount of A is always equal to one-half of the quantity of A you had at the beginning of the round. The program will not allow you to have less than the minimum amount.

For example if you start a round with 34 units of A, you have to end round with at least 17 units of A.

As another example, suppose you have 11 units of A at the beginning of a round. You can make for example:

12.13 units of A and 1 unit of X or 7.2 units of A and 5.93 units of X or 6 units of A and 7.13 units of X or 5.5 units of A and 7.63 units of X

For all of these combinations the total adds up to 13.13 and includes at least 5.5 units of A.

Now refer to the Token Value Sheet for X.

You receive tokens for the X you produce in every round of every game. After you receive tokens for X in a round, you lose the X that you currently have. You can think of this as "cashing in" your units of X for tokens each round. You can receive tokens for X in subsequent rounds only by producing more X in subsequent rounds.

On the token value sheets, the first column contains the number of units that you made in the round.

The last column, entitled Total Value, contains the TOTAL number of tokens you receive from those units.

The second column, entitled Additional Value, contains the additional number of tokens that you receive from the last unit you made. For example, in row 5, the number in the Additional Value column gives the additional number of tokens you receive from making 5 units instead of making 4 units.

SUMMARY

A. There will be 20 total games consisting of a series of rounds.

B. You start each game with 3 units of A.

C. The number of rounds in a game will be determined by chance. A game always has a 10 percent chance of ending in a given round.

D. In each round you can produce X and A from the current amount of A that you have.

E. The X that you produce gives you "tokens" which can be converted to US dollars at the rate of 700 tokens to 1 dollar. X does not carry over from round to round.

F. The A that you produce allows you to produce more X in future rounds. A carries over from round to round.

Table 1: Parameters for the Basic Design

Treatment	k_0	α	ϕ	δ	ρ	η	γ	steady state $\bar{k}$	steady state $\bar{c}$
Fast/Low	3	0.2	25.23	0.5	1/9	100	1	14	35.78
Slow/Low	3	0.9	0.88	0.5	1/9	100	1	14	2.51
Fast/High	50	0.2	25.23	0.5	1/9	100	1	14	35.78
Slow/High	50	0.9	0.88	0.5	1/9	100	1	14	2.51

Table 2: Summary of Data Gathered

Treatment	Num.Subj.	Endowment	Prod.Func.	Ending Rule	Location
Slow/Low	11	3	$.884k_t^{.9}$	Random	Purdue
Slow/High	10	50	$.884k_t^{.9}$	Random	Purdue
Fast/Low	10	3	$25.23k_t^{.2}$	Random	Purdue
Fast/High	11	50	$25.23k_t^{.2}$	Random	Purdue
Slow/Low/Fixed	12	3	$.884k_t^{.9}$	Fixed	Purdue
Slow/Low/Japan	6	3	$.884k_t^{.9}$	Random	Waseda
Slow/High/Japan	5	3	$.884k_t^{.9}$	Random	Waseda

Table 3: Optimal Trajectories

$k_0 = 3$

	Fast/Low $\alpha = 0.2, \phi = 25.23$		Slow/Low $\alpha = 0.9, \phi = 0.884$	
Round	k_t ($\bar{k} = 14$)	c_t ($\bar{c} = 35.78$)	k_t ($\bar{k} = 14$)	c_t ($\bar{c} = 2.51$)
1	3.00	24.43	3.00	0.36
2	8.51	31.28	3.51	0.48
3	11.69	34.03	4.02	0.58
4	13.08	35.10	4.52	0.69
5	13.64	35.52	5.00	0.79
6	13.86	35.68	5.48	0.89
7	13.95	35.74	5.94	0.98
8	13.98	35.76	6.38	1.07
9	13.99	35.77	6.81	1.15
10	14.00	35.78	7.22	1.23
11	14.00	35.78	7.62	1.31
12	14.00	35.78	8.00	1.38
13	14.00	35.78	8.35	1.45
14	14.00	35.78	8.70	1.52
15	14.00	35.78	9.02	1.58
16	14.00	35.78	9.33	1.64
17	14.00	35.78	9.62	1.70
18	14.00	35.78	9.90	1.75
19	14.00	35.78	10.16	1.80
20	14.00	35.78	10.41	1.84
21	14.00	35.78	10.64	1.89

$k_0 = 50$

	Fast/High $\alpha = 0.2, \phi = 25.23$		Slow/High $\alpha = 0.9, \phi = 0.884$	
Round	k_t ($\bar{k} = 14$)	c_t ($\bar{c} = 35.78$)	k_t ($\bar{k} = 14$)	c_t ($\bar{c} = 2.51$)
1	50.00	54.65	50.00	8.57
2	25.53	42.97	46.32	7.98
3	18.04	38.53	43.09	7.45
4	15.49	36.83	40.24	6.99
5	14.57	36.18	37.72	6.57
6	14.22	35.93	35.48	6.20
7	14.08	35.84	33.49	5.87
8	14.03	35.80	31.71	5.58
9	14.01	35.79	30.12	5.31
10	14.00	35.78	28.70	5.07
11	14.00	35.78	27.42	4.85
12	14.00	35.78	26.26	4.66
13	14.00	35.78	25.22	4.48
14	14.00	35.78	24.28	4.32
15	14.00	35.78	23.43	4.17
16	14.00	35.78	22.65	4.04
17	14.00	35.78	21.95	3.91
18	14.00	35.78	21.31	3.80
19	14.00	35.78	20.73	3.70
20	14.00	35.78	20.19	3.61
21	14.00	35.78	19.71	3.52

Table 4: End of Period Capital Stock Holdings Relative to Optimum by Treatment: Last Five Periods:

All Subjects

Treatment	Greater than Predicted	Less than Predicted	Total Observations	Prob(Greater and Less Equally Likely)
S/L	8	47	55	$p < 10^{-7}$
S/H	7	43	50	$p < 10^{-6}$
F/L	28	22	50	$p = .2399$
F/H	35	20	55	$p < .05$
S/L/F	15	45	60	$p < .05$
S/L/W	1	29	30	$p < 10^{-7}$
S/H/W	10	15	25	$p = .212$

Table 5: Instances of Monotone Increase, Monotone Decrease, and Binging Behavior: Last Five Periods: All Treatments

Treatment	Total Obs.	Mon. Inc.	Mon. Dec.	Binge
Low/Slow	55	14	30	12
High/Slow	50	0	34	19
Low/Fast	50	8	1	19
High/Fast	55	1	38	34
Low/Slow/Fixed	60	12	24	10
Low/Slow/Waseda	30	5	13	5
High/Slow/Waseda	25	0	25	3

Note: An observation may be classified as both a Monotonic Decrease and as a Binge.

Table 6: Error Components Estimates of Efficiency of Different Treatments: All Periods

	Treatment					
	Slow/Low	High	Fast	HighFast	Fixed	Waseda
Effect	.713	.083	.182	-.038	.095	.091
	(.031)	(.040)	(.047)	(.063)	(.046)	(.042)

Table 7: Observed Efficiency as a Function of Period Number and Length and Overall Average

Treatment	constant	Periods	Rounds	Overall Avg.
S/L	1.7*	-.004	−.058*	.713
	(.122)	(.006)	(.005)	
S/H	.917*	.004	−.011*	.796
	(.062)	(.003)	(.002)	
F/L	.769*	.003	.007*	.895
	(.049)	(.002)	(.001)	
F/H	.916*	.003*	0	.940
	(.018)	(.001)	(.001)	
S/L/F	.73*	.007*	-	.808
	(.046)	(.001)		
S/L/W	1.69*	.002	−.056*	.805
	(.137)	(.009)	(.006)	
S/H/W	1.03*	.002	−.011*	.885
	(.056)	(.003)	(.002)	

Note: An asterisk indicates significance at less than the 5 percent level.

Figure 1. Phase Diagram

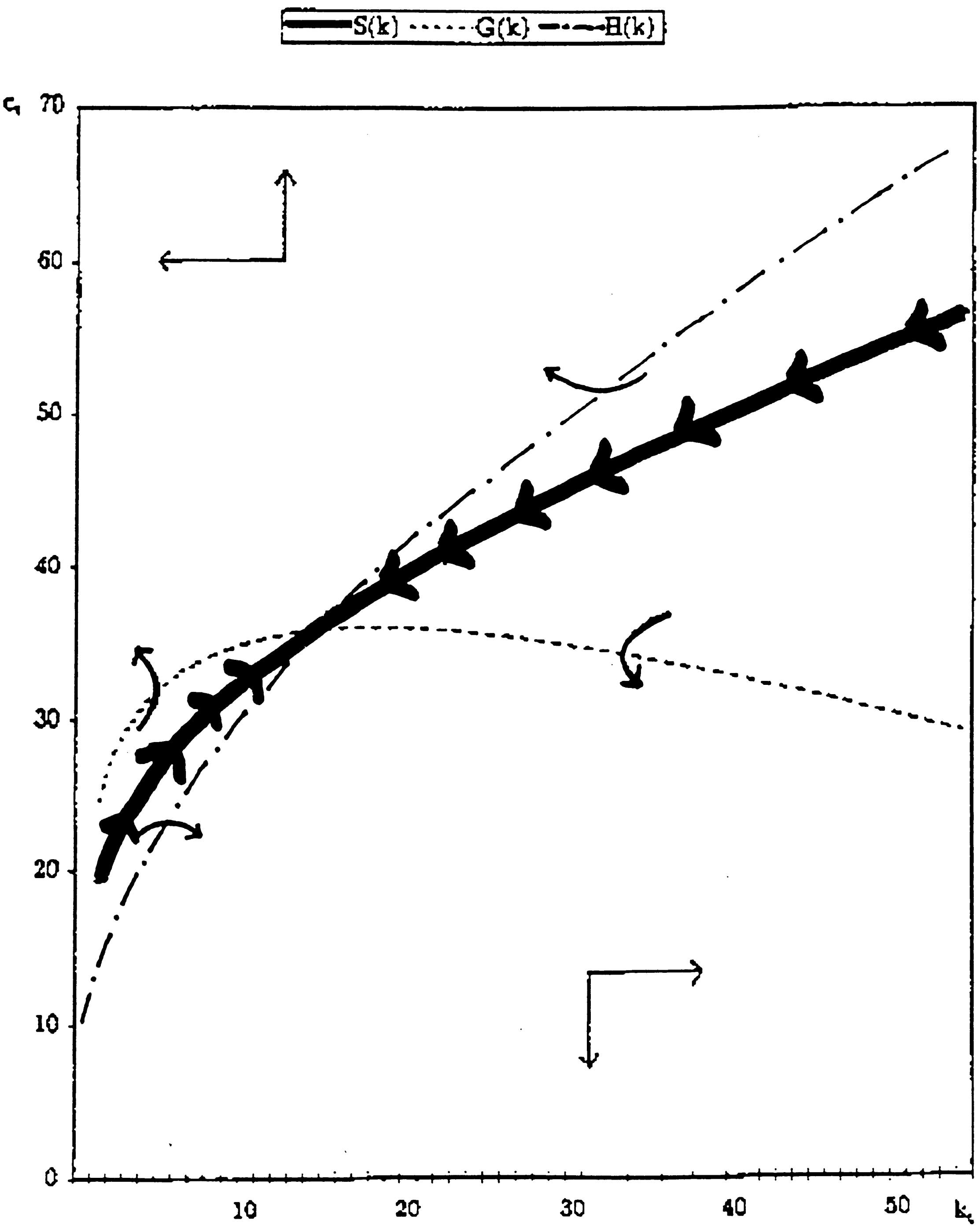


Figure 2a: Capital Stock Holdings in the Slow/Low Treatment: Period 5: All Subjects

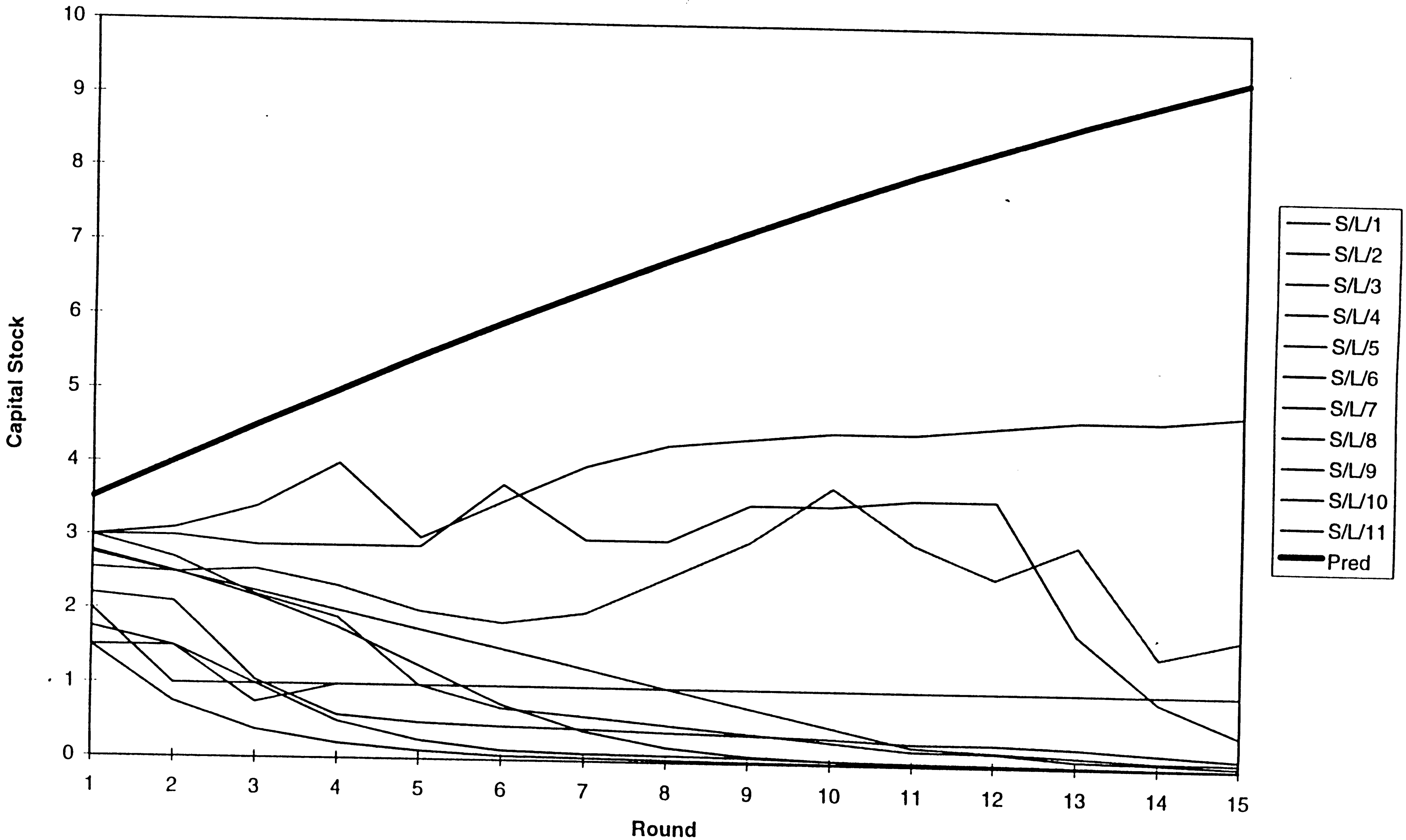


Figure 2b: Capital Stock Holdings in the Slow/Low Treatment: Period 19: All Subjects

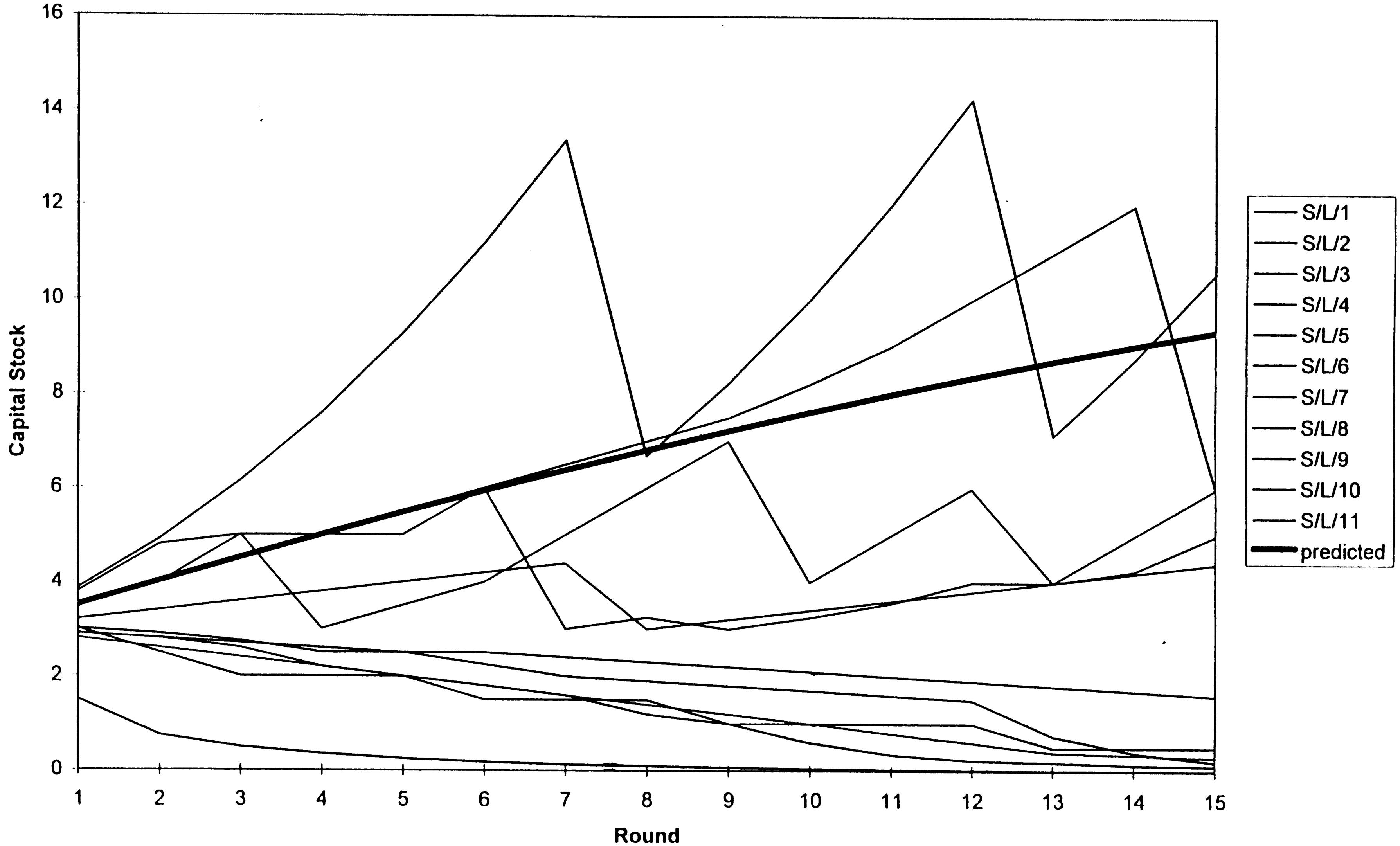


Figure 3a: Capital Stock Holdings In the Slow/High Treatment: Period 5: All Subjects

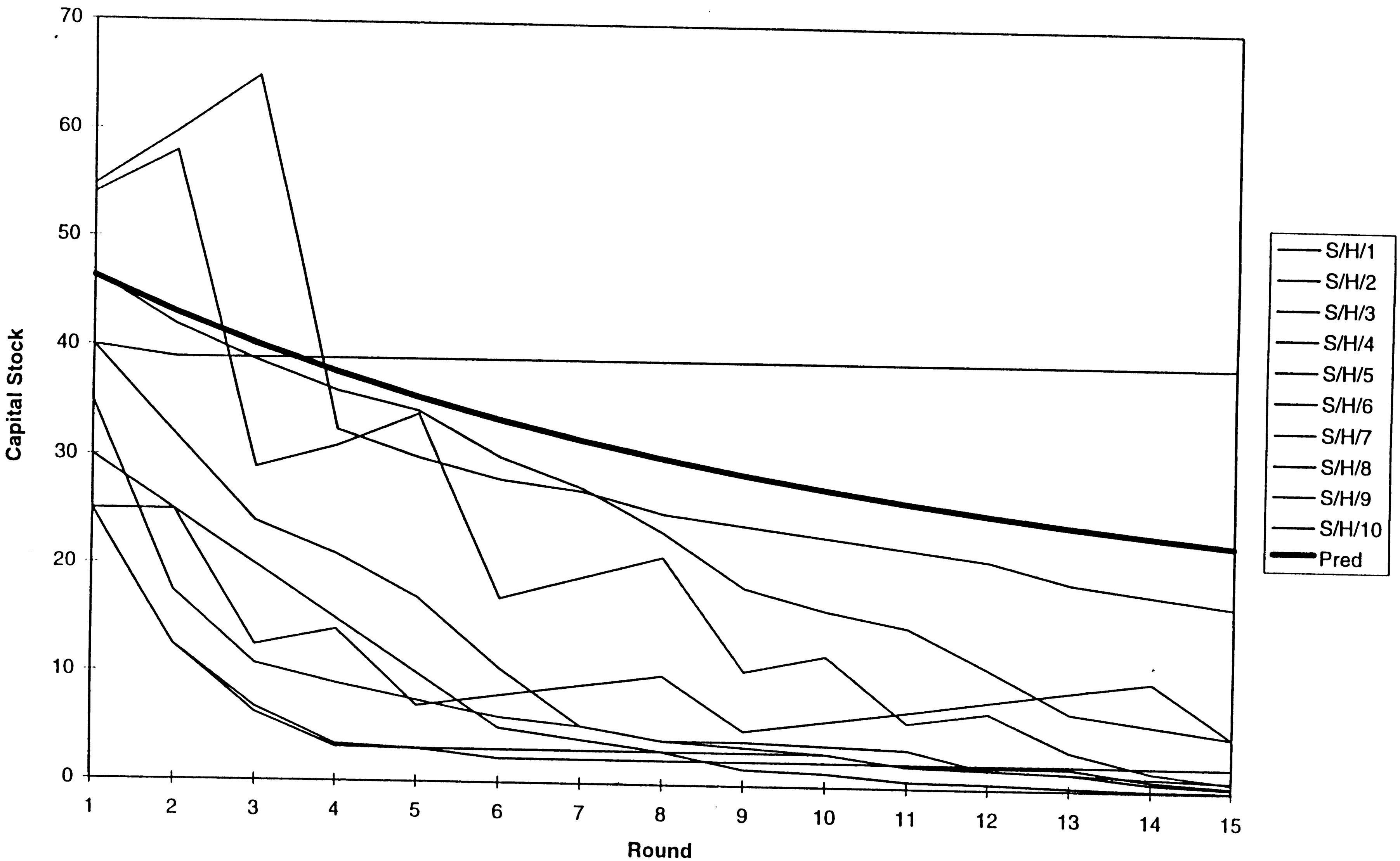


Figure 3b: Capital Stock Holdings in the Slow/High Treatment: Period 19: All Subjects

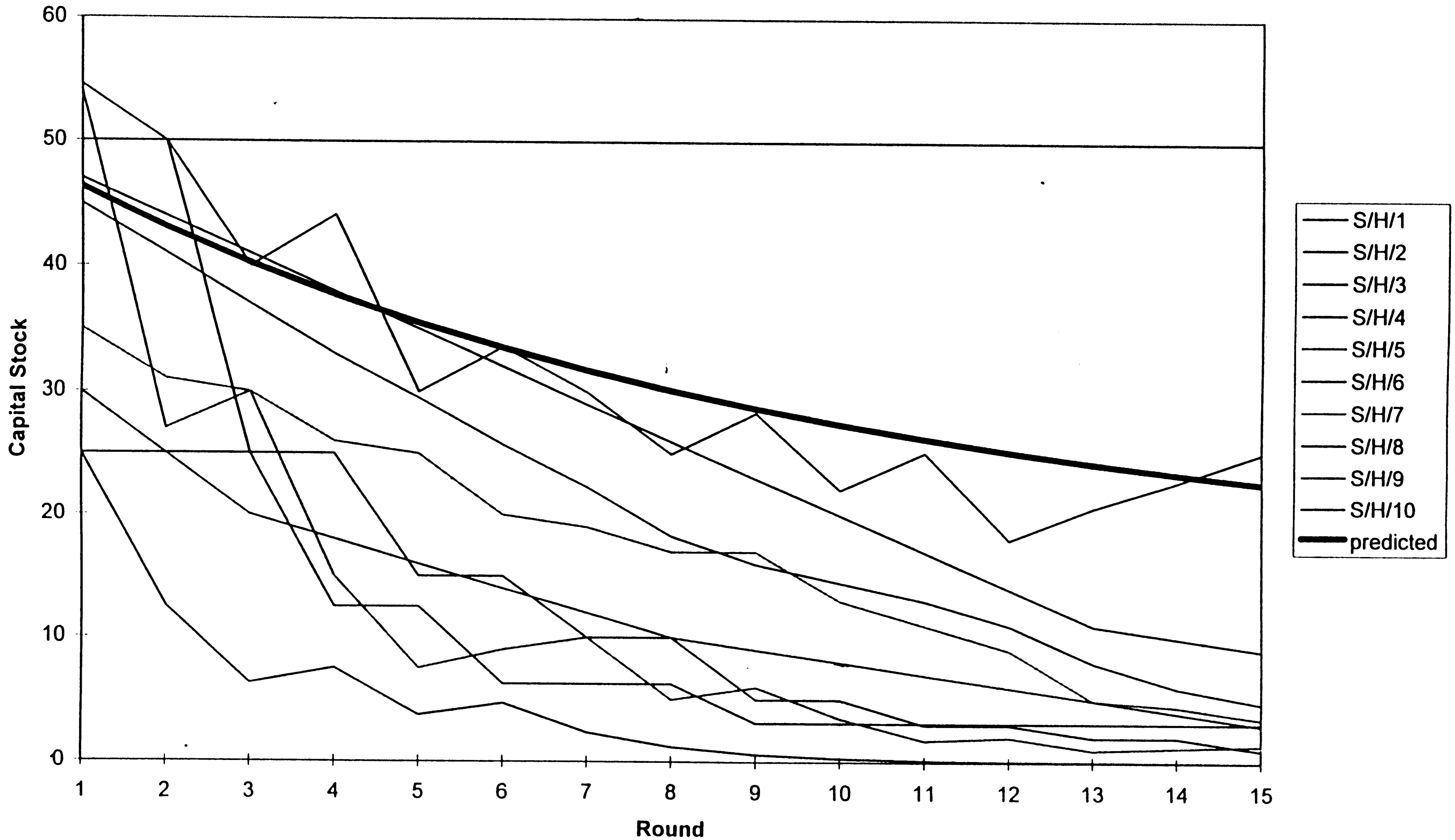


Figure 4a: Capital Stock Holdings In the Fast/Low Treatment: Period 5: All Subjects

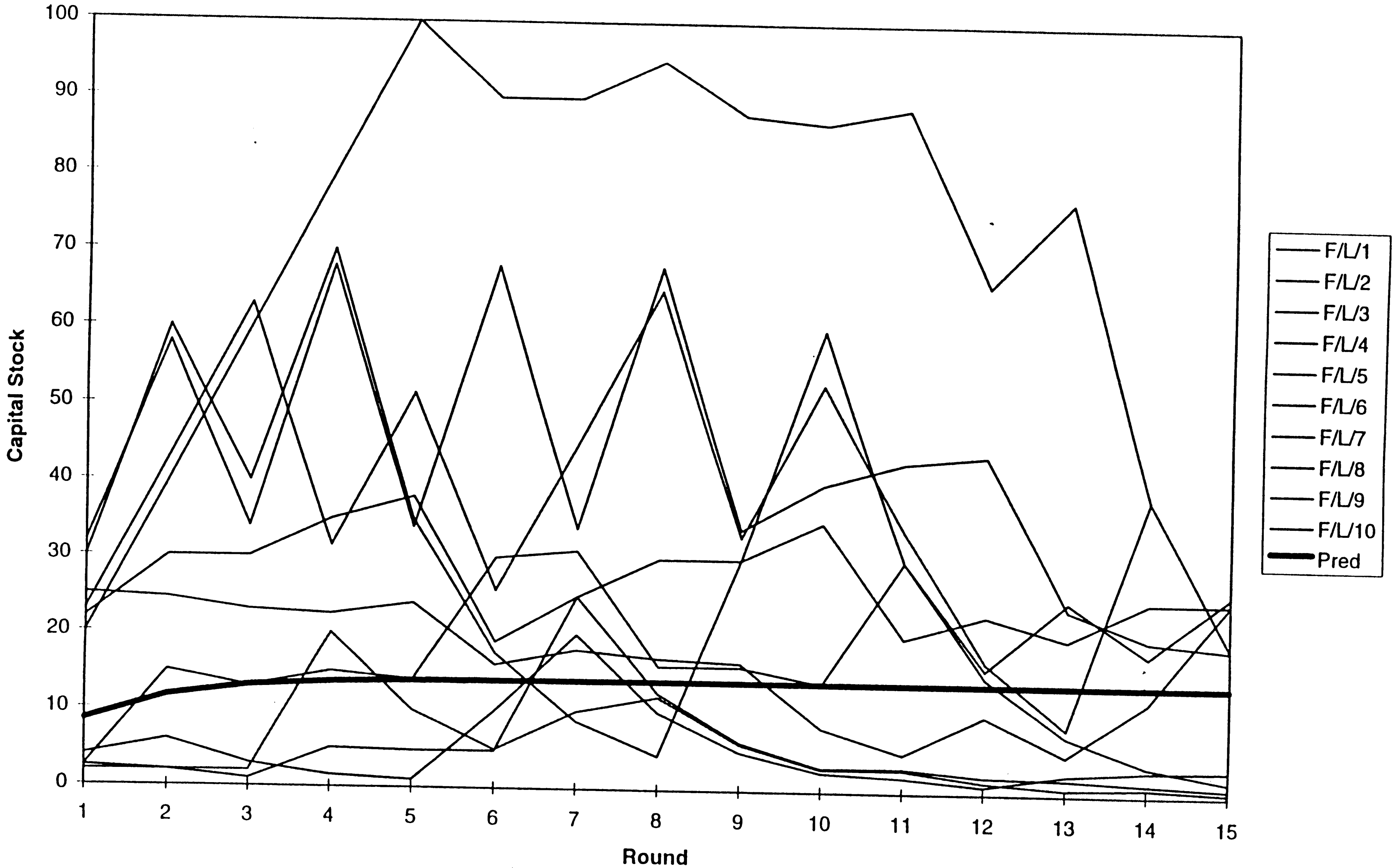


Figure 4b: Capital Stock Holdings in the Fast/Low Treatment: Period 19: All Subjects

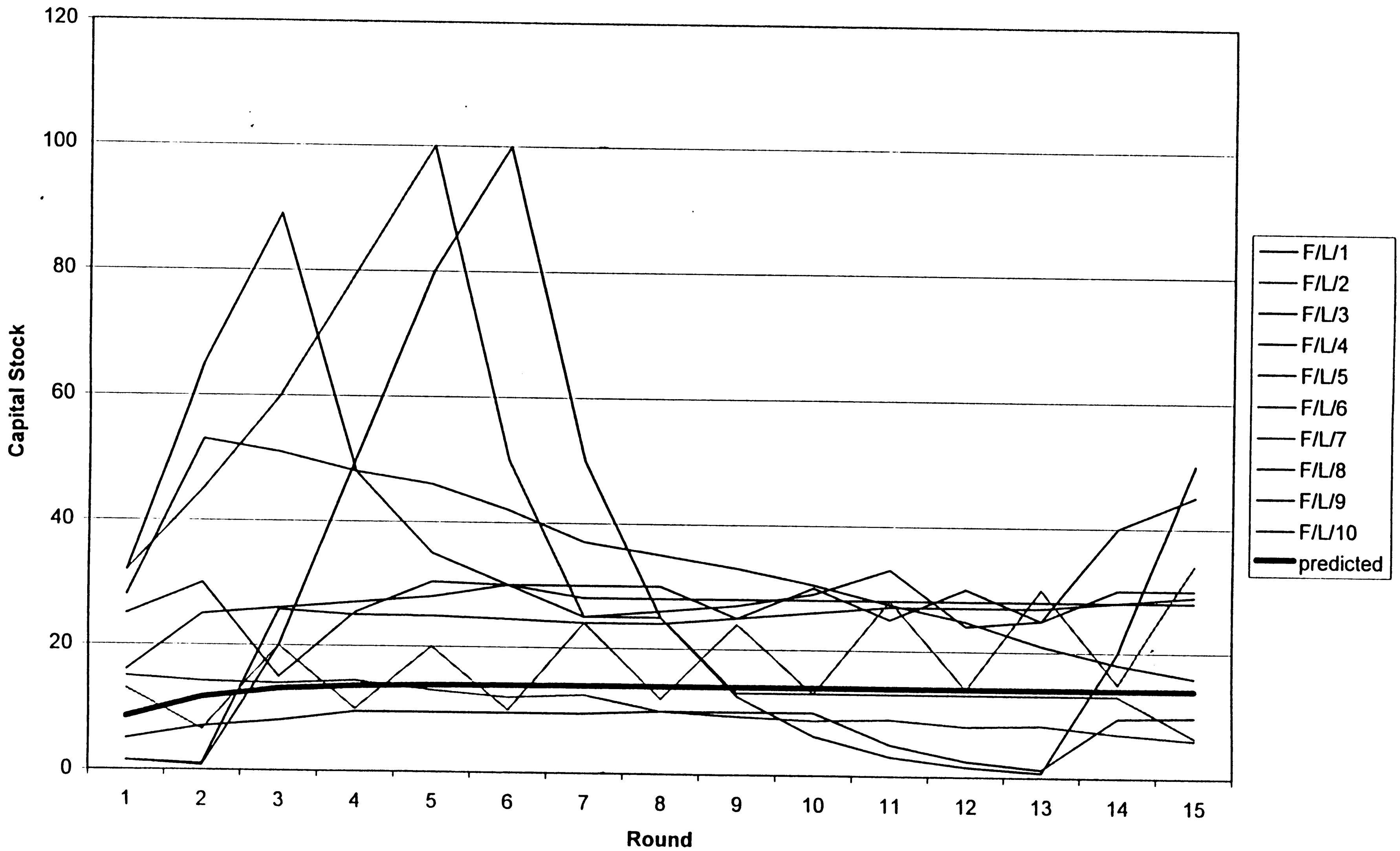


Figure 5a: Capital Stock Holdings in the Fast/High Treatment: Period 5: All Subjects

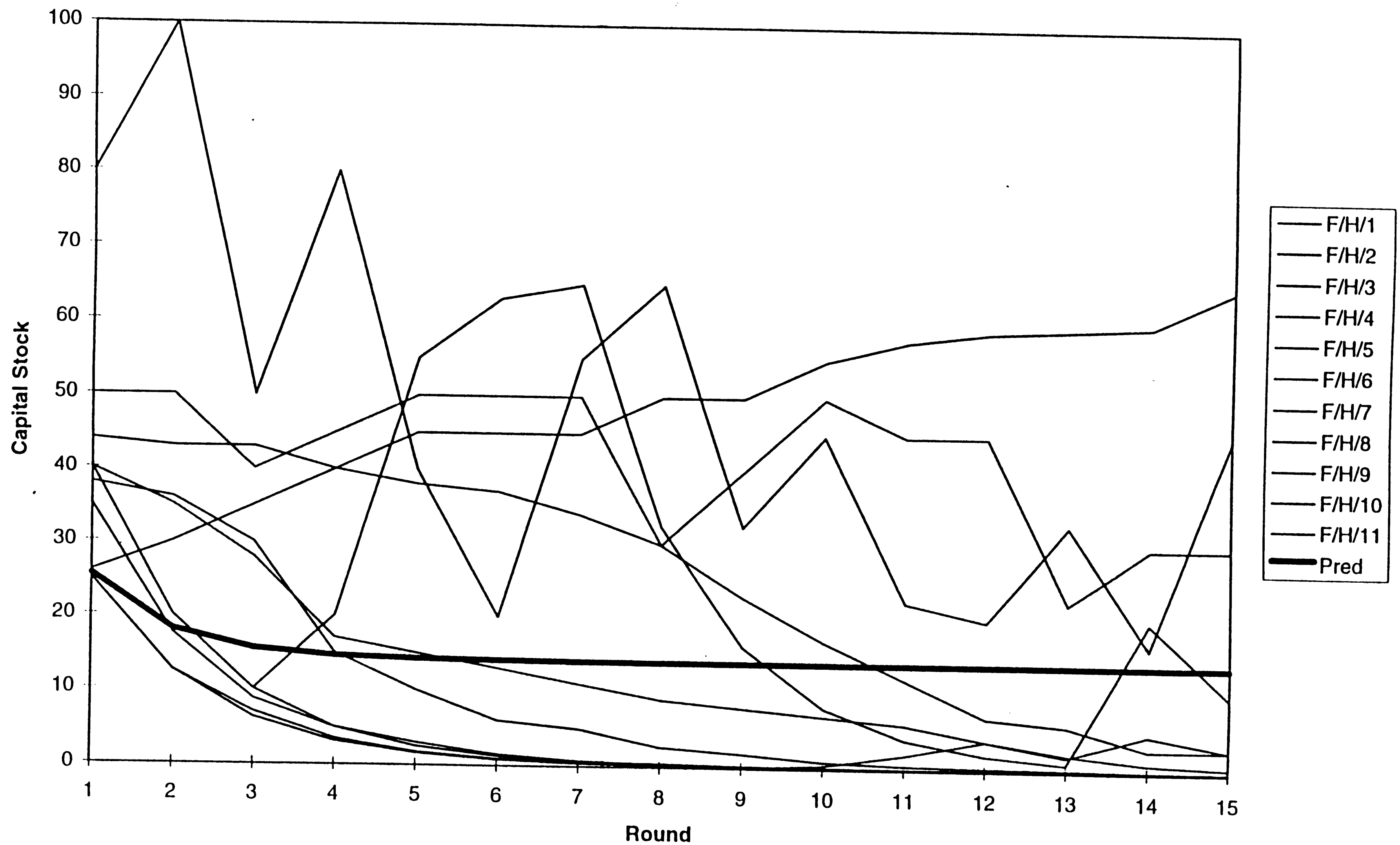


Figure 5b: Capital Stock Holdings in the Fast/High Treatment: Period 19: All Subjects

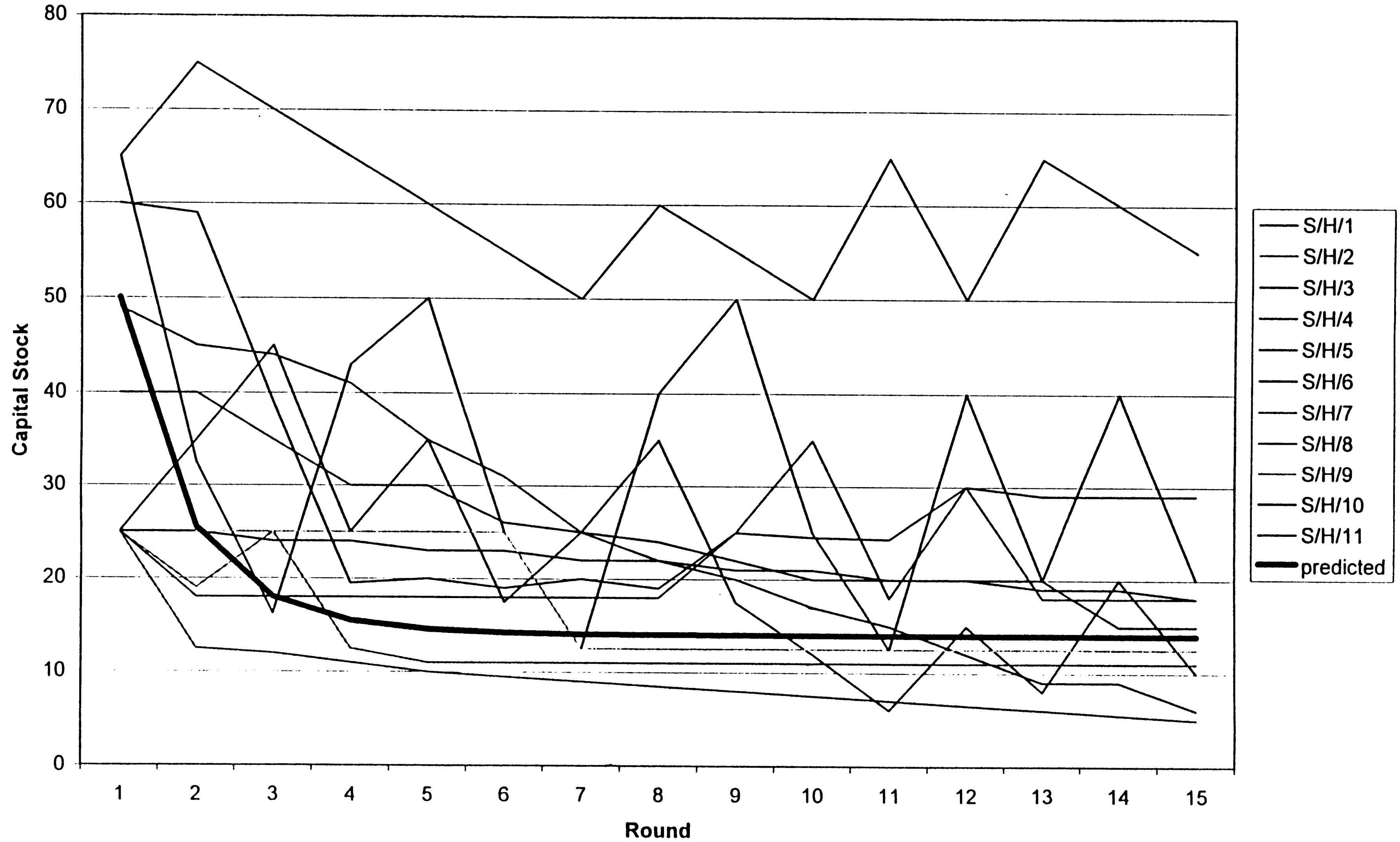


Figure 6a: Capital Stock Holdings in the Slow/Low/Fixed Treatment: Period 5: All Subjects

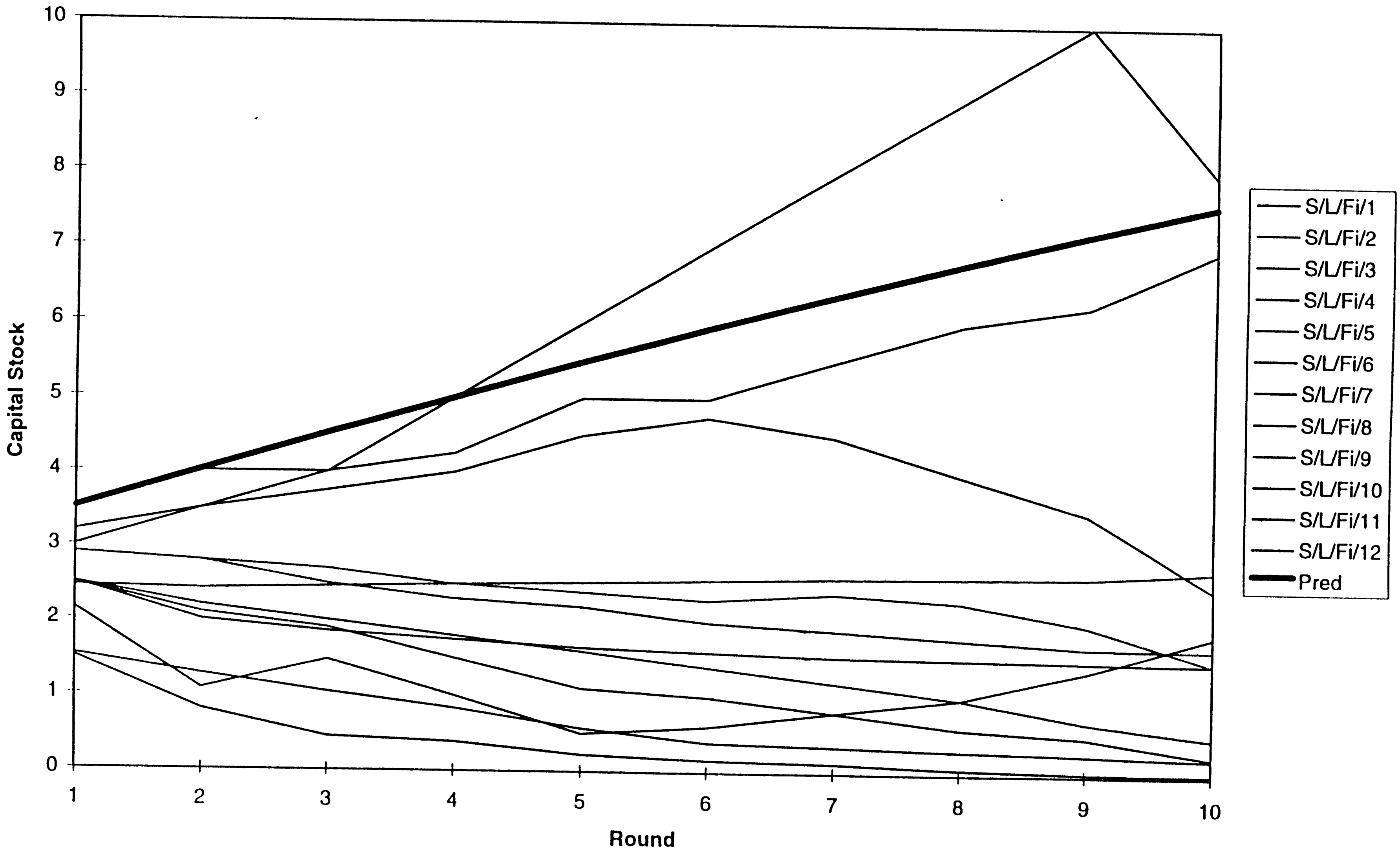


Figure 6b: Capital Stock Holdings in the Slow/Low/Fixed Treatment: Period 19: All Subjects

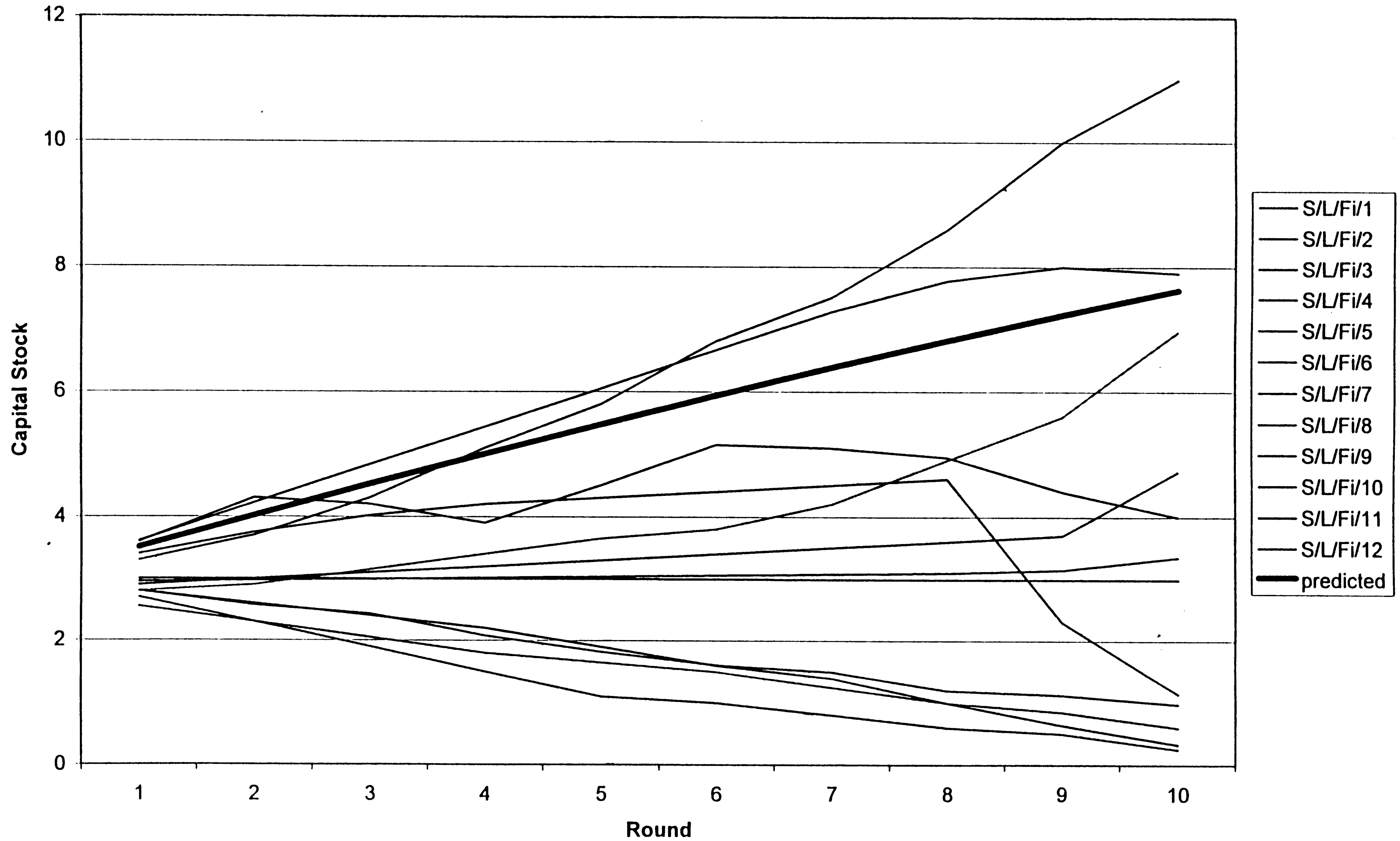


Figure 7a: Capital Stock Holdings in the Slow/Low/Waseda Treatment: Period 5: All Subjects

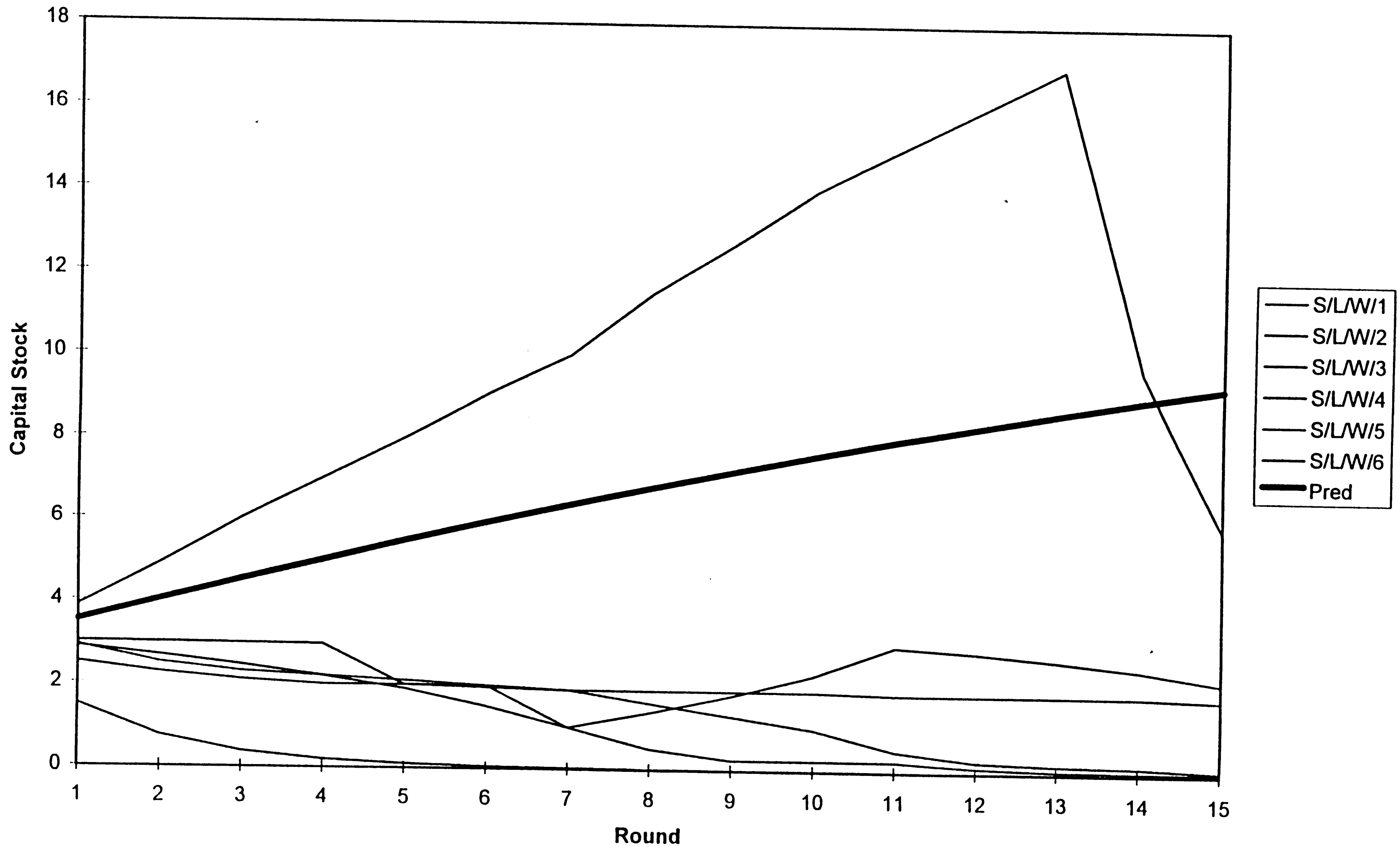


Figure 7b: Capital Stock Holdings in the Slow/Low/Waseda Treatment: Period 19: All Subjects

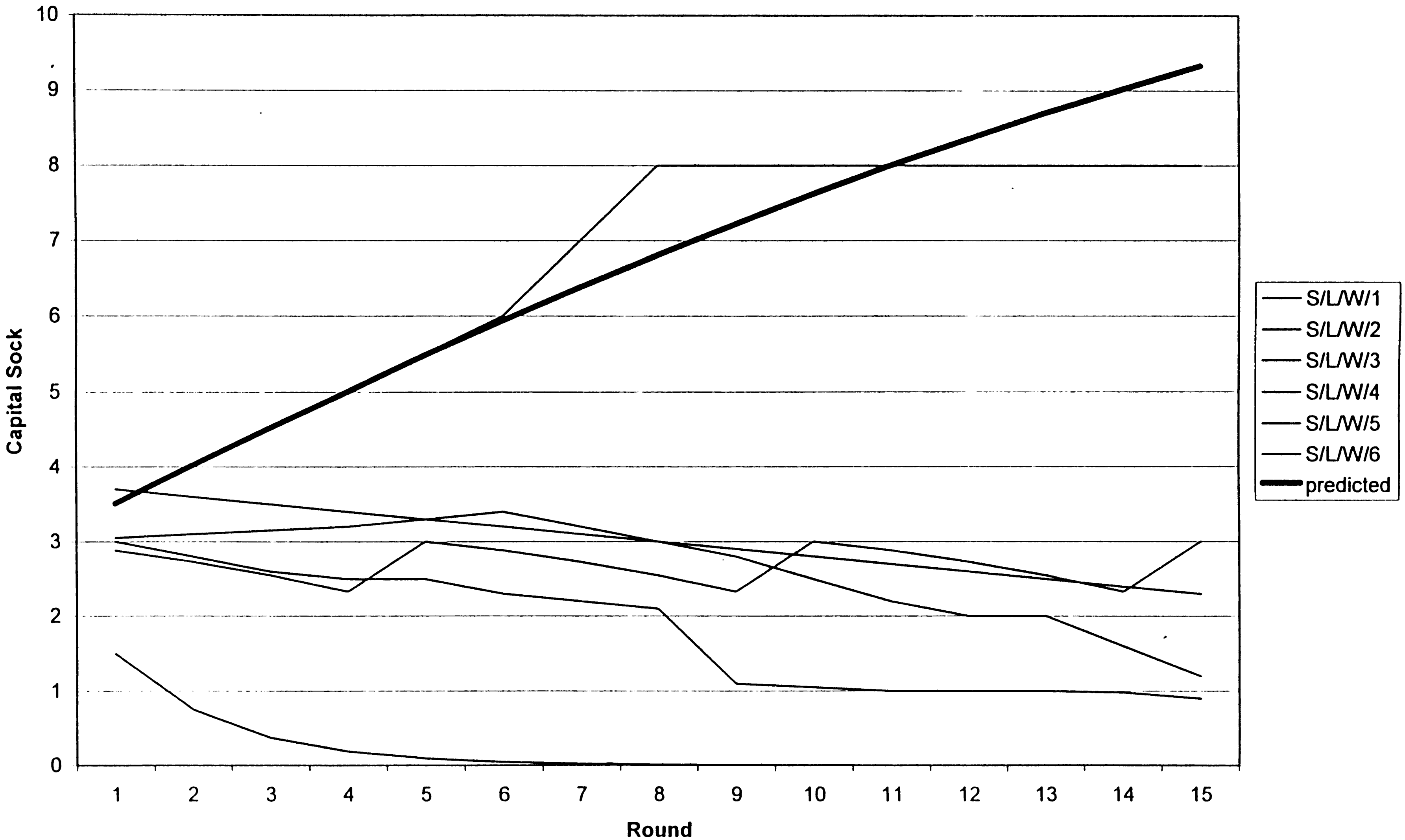


Figure 8a: Capital Stock Holdings in the Slow/High/Waseda Treatment: Period 5: All Subjects

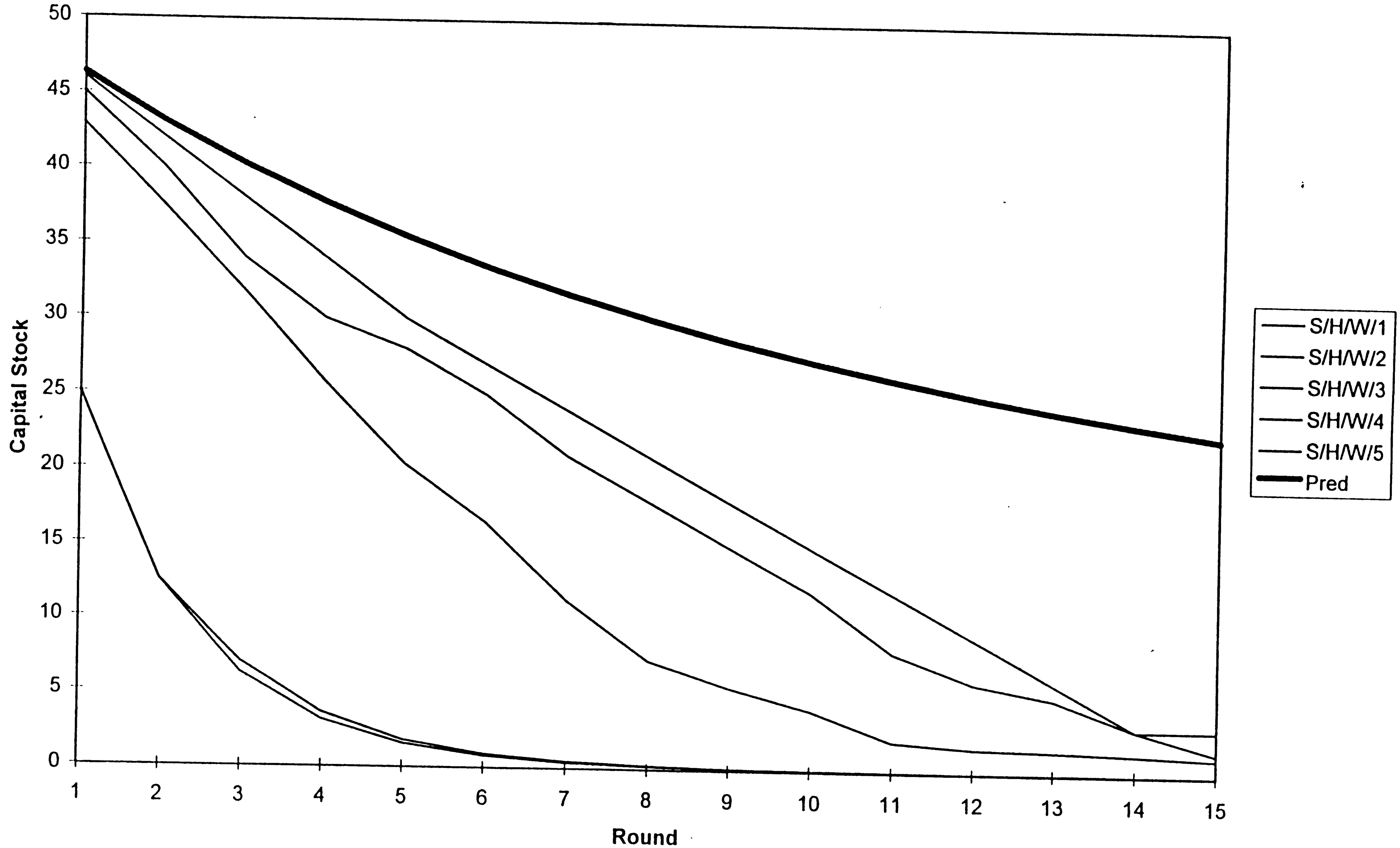


Figure 8b: Capital Stock Holdings in the Slow/High/Waseda Treatment: Period 19: All Subjects

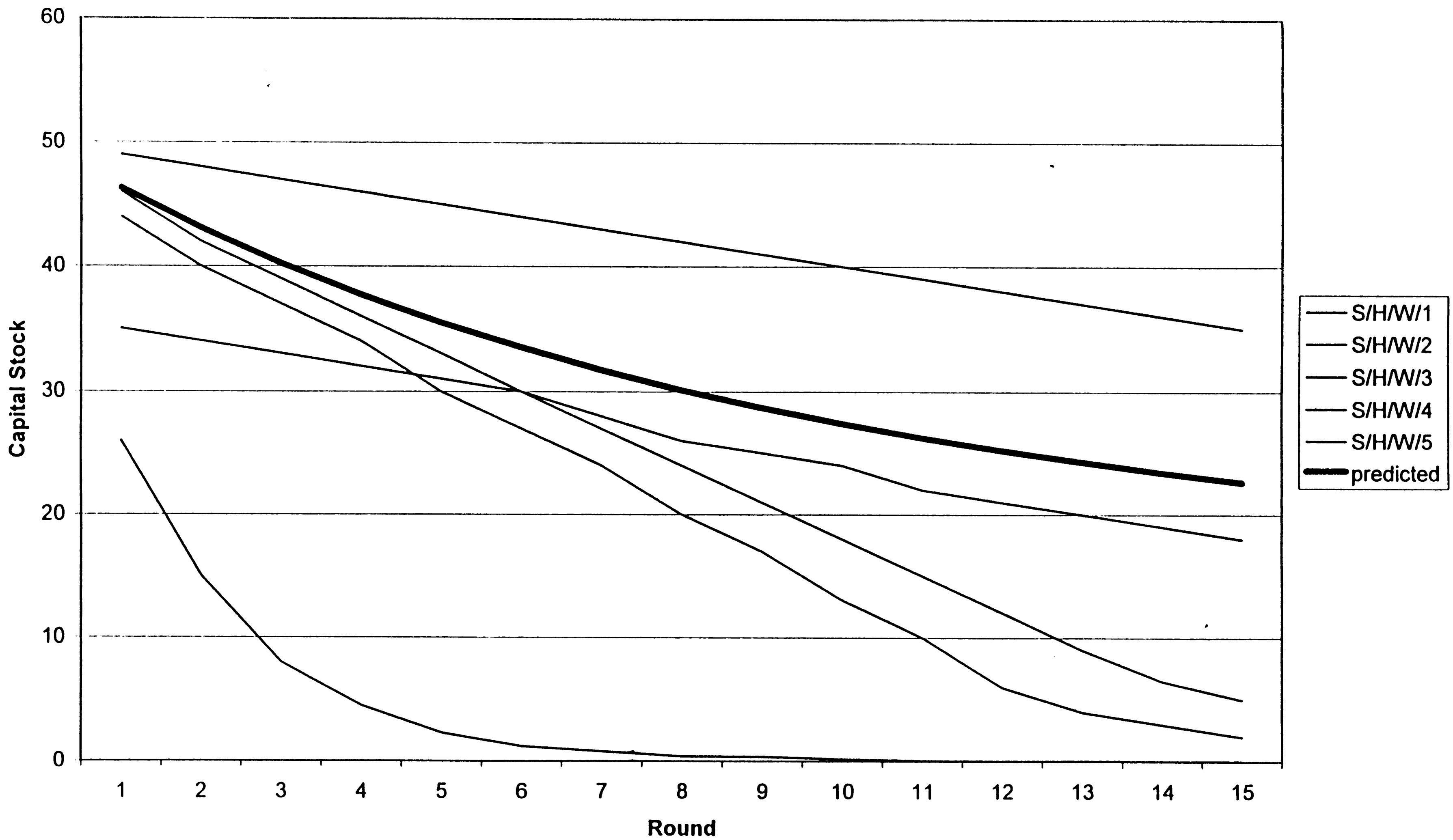


Figure 9: Consumption in the Slow/Low treatment: Period 19: All Subjects

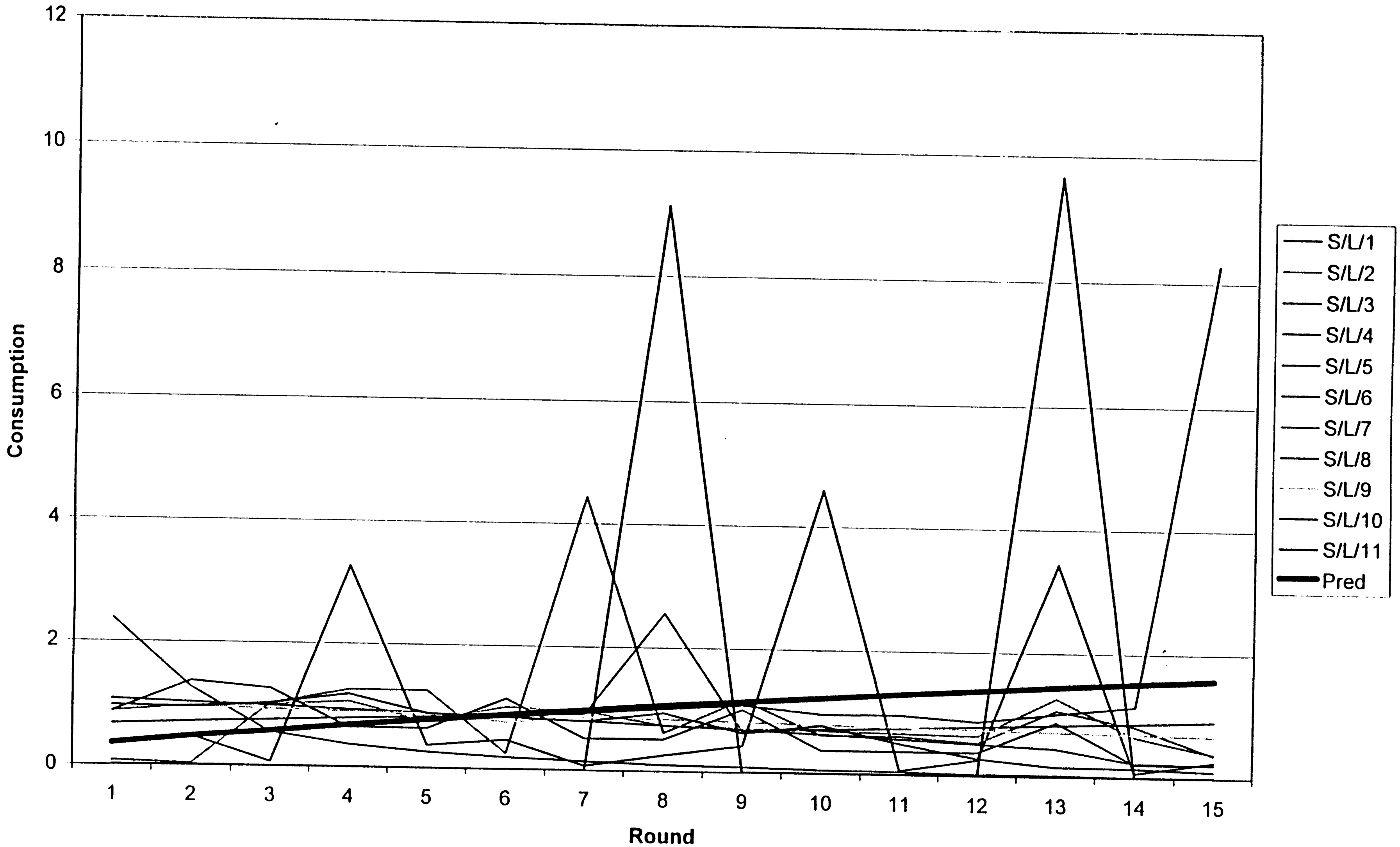


Figure 10: Consumption in the Slow/High Treatment: Period 19: All Subjects

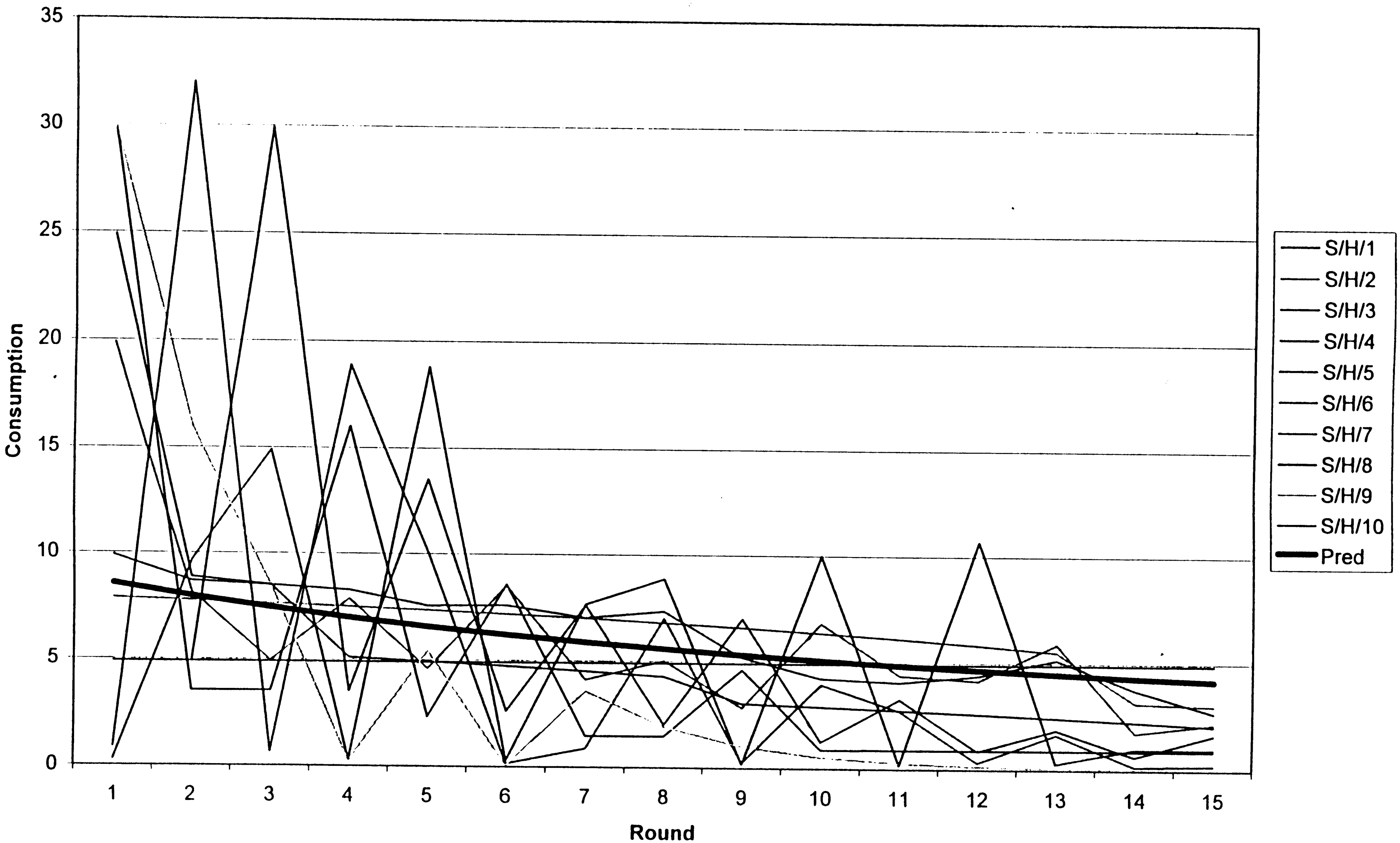


Figure 11: Consumption in the Fast/Low Treatment: Period 19: All Subjects

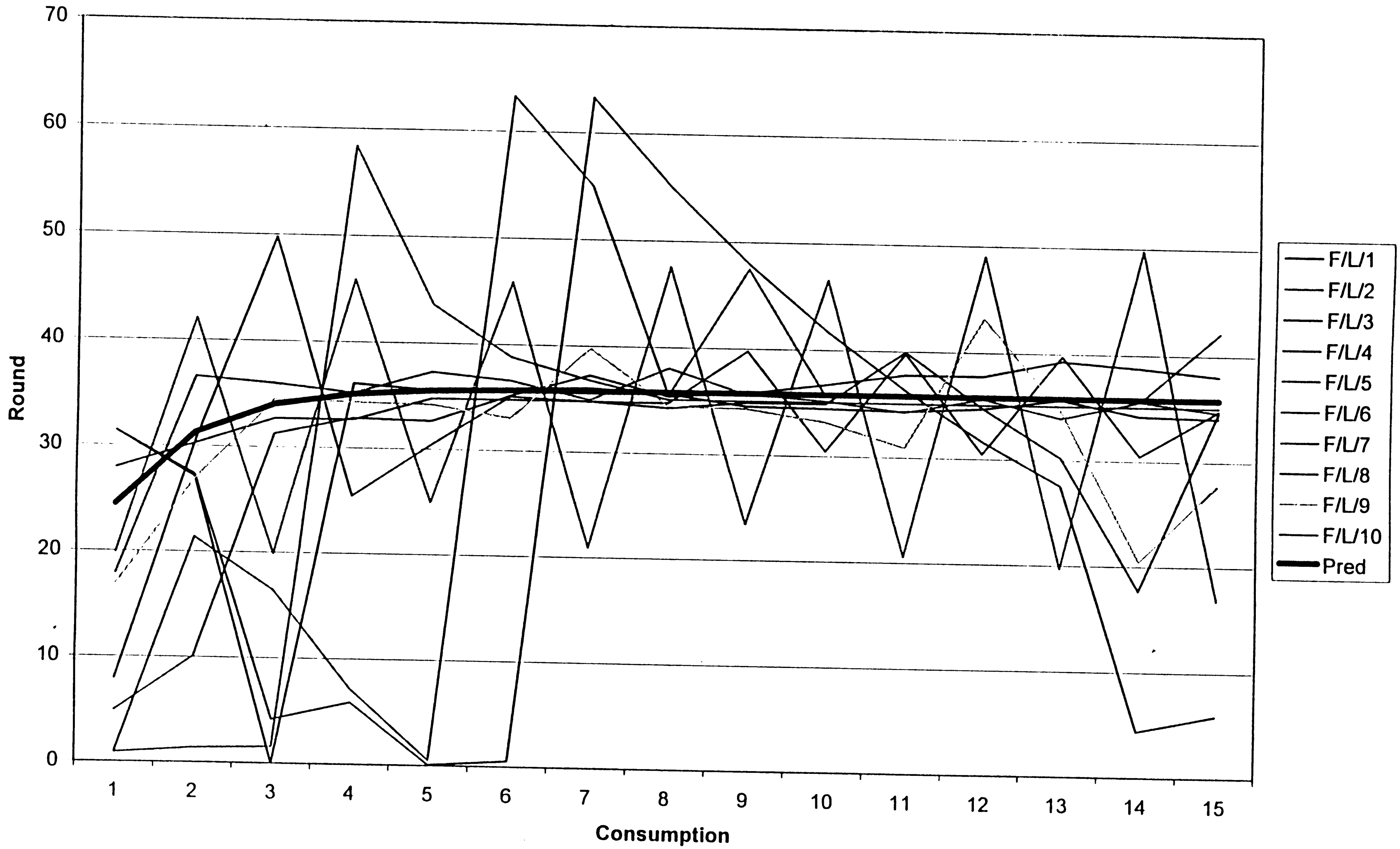


Figure 12: Consumption in the Fast/High Treatment: Period 19: All Subjects

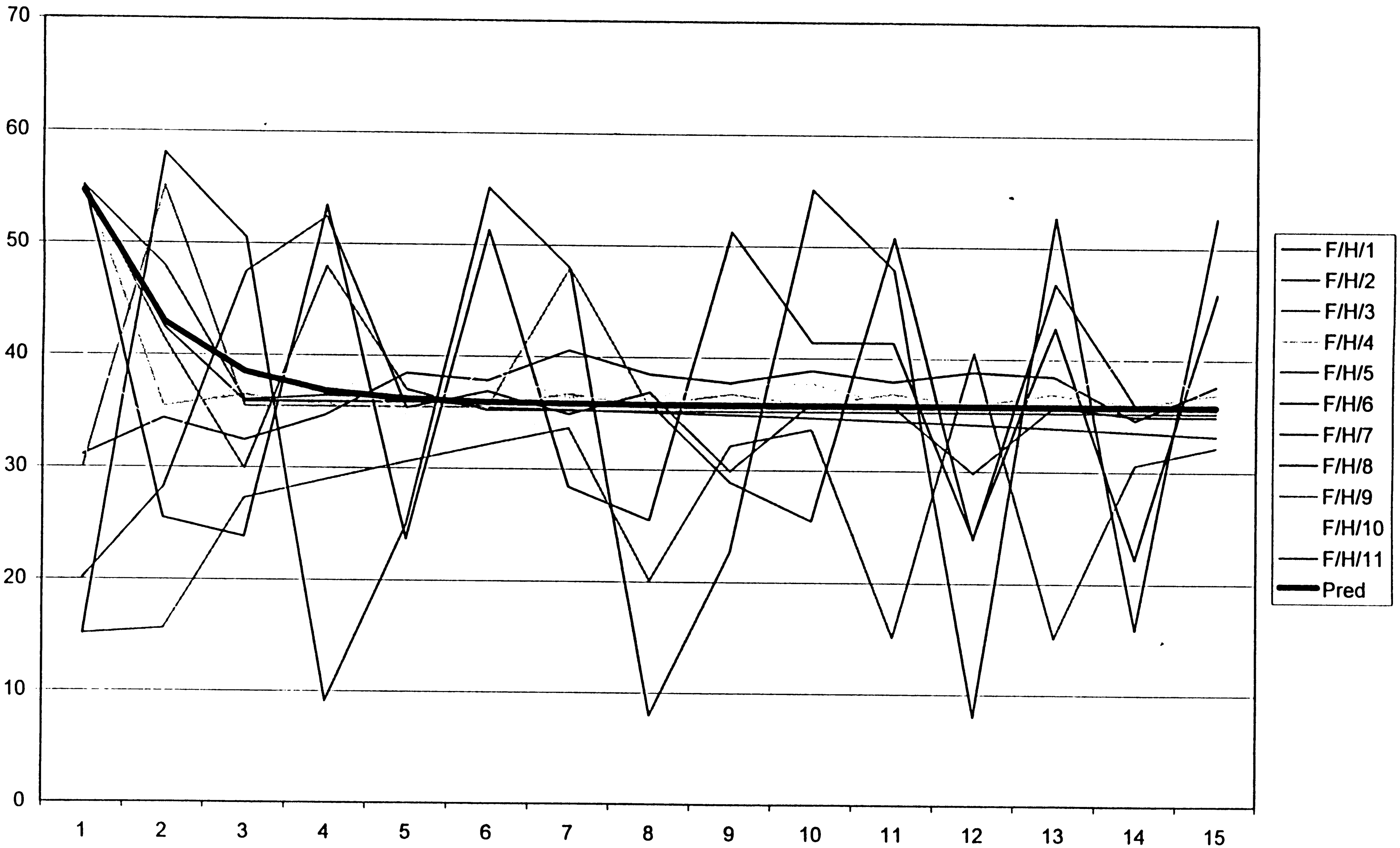


Figure 13: Consumption in the Slow/Low/Fixed Treatment: Period 19: All Subjects

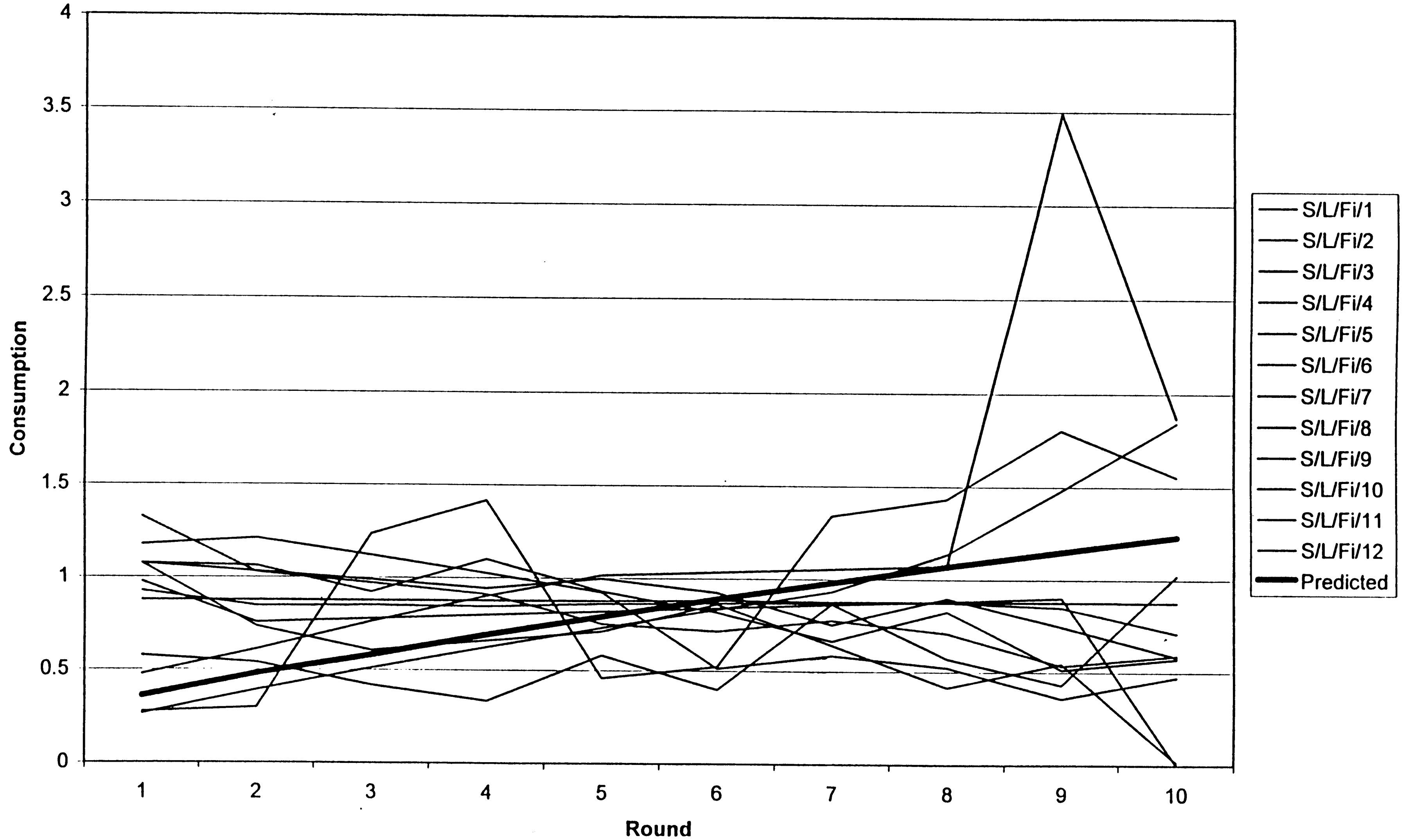


Figure 14: Consumption in the Slow/Low/Waseda Treatment: Period 19: All Subjects

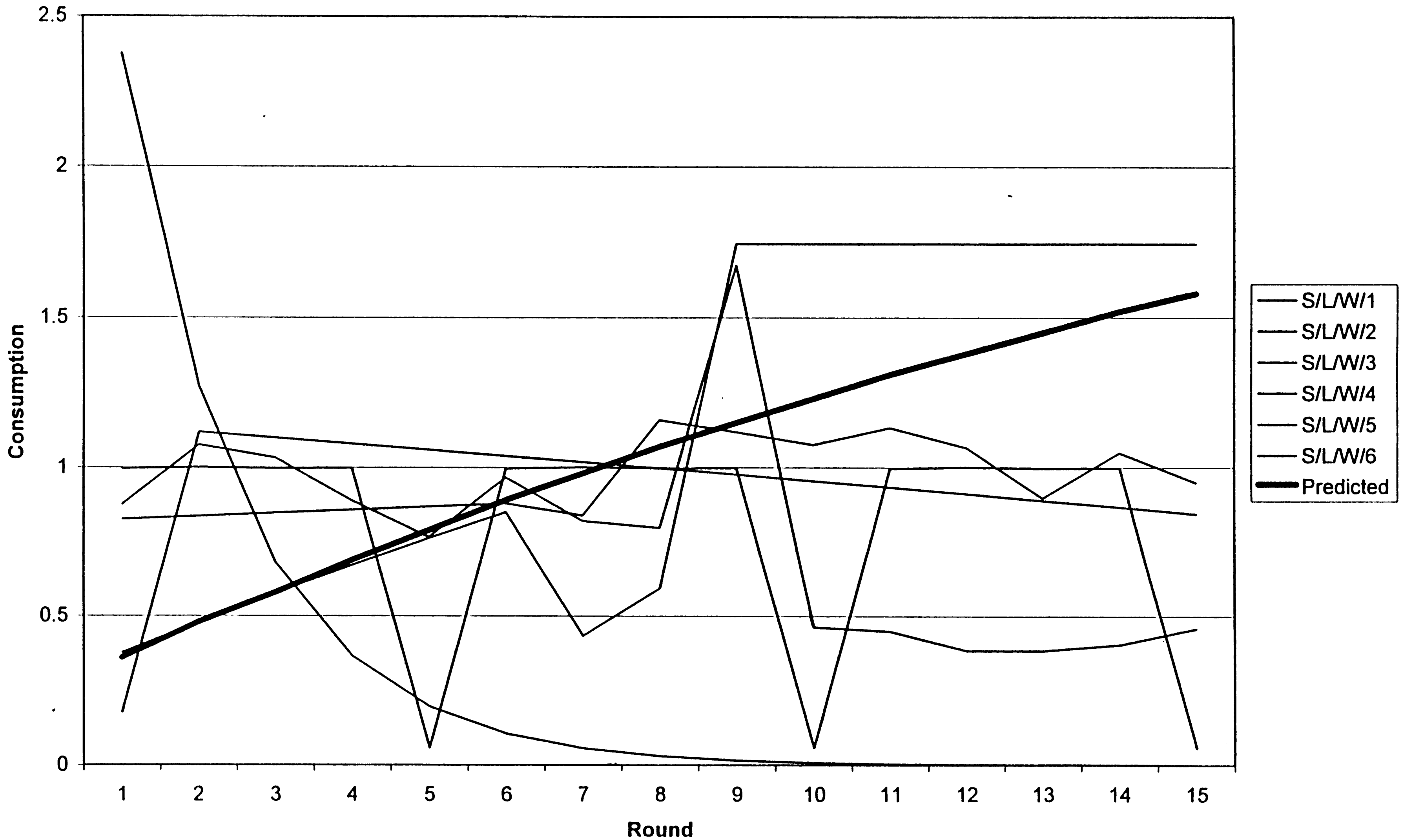
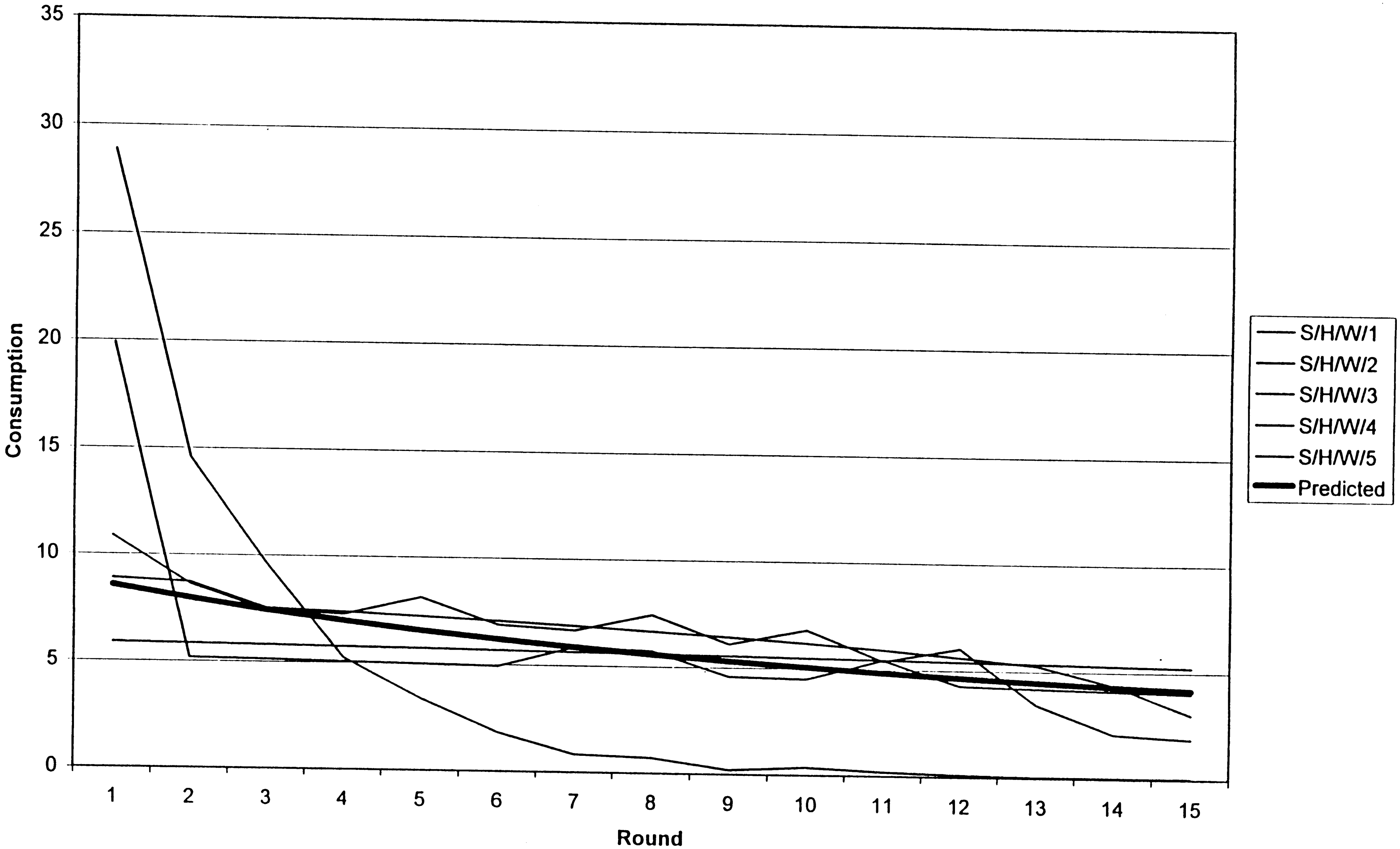


Figure 15: Consumption in the Slow/High/Waseda Treatment: Period 19: All Subjects



Token Value for X

Total # of Units	Additional Value of Last Tenth of a Unit	Total Value	Total # of Units	Additional Value of Last Tenth of a Unit	Total Value
1	69.315	69.315	51	1.942	395.124
2	40.547	109.861	52	1.905	397.029
3	28.768	138.629	53	1.869	398.898
4	22.314	160.944	54	1.835	400.733
5	18.232	179.176	55	1.802	402.535
6	15.415	194.591	56	1.770	404.305
7	13.353	207.944	57	1.739	406.044
8	11.778	219.722	58	1.709	407.754
9	10.536	230.259	59	1.681	409.434
10	9.531	239.790	60	1.653	411.087
11	8.701	248.491	61	1.626	412.713
12	8.004	256.495	62	1.600	414.313
13	7.411	263.906	63	1.575	415.888
14	6.899	270.805	64	1.550	417.439
15	6.454	277.259	65	1.527	418.965
16	6.062	283.321	66	1.504	420.469
17	5.716	289.037	67	1.482	421.951
18	5.407	294.444	68	1.460	423.411
19	5.129	299.573	69	1.439	424.850
20	4.879	304.452	70	1.418	426.268
21	4.652	309.104	71	1.399	427.667
22	4.445	313.549	72	1.379	429.046
23	4.256	317.805	73	1.361	430.407
24	4.082	321.888	74	1.342	431.749
25	3.922	325.810	75	1.325	433.073
26	3.774	329.584	76	1.307	434.381
27	3.637	333.220	77	1.290	435.671
28	3.509	336.730	78	1.274	436.945
29	3.390	340.120	79	1.258	438.203
30	3.279	343.399	80	1.242	439.445
31	3.175	346.574	81	1.227	440.672
32	3.077	349.651	82	1.212	441.884
33	2.985	352.636	83	1.198	443.082
34	2.899	355.535	84	1.183	444.265
35	2.817	358.352	85	1.170	445.435
36	2.740	361.092	86	1.156	446.591
37	2.667	363.759	87	1.143	447.734
38	2.598	366.356	88	1.130	448.864
39	2.532	368.888	89	1.117	449.981
40	2.469	371.357	90	1.105	451.086
41	2.410	373.767	91	1.093	452.179
42	2.353	376.120	92	1.081	453.260
43	2.299	378.419	93	1.070	454.329
44	2.247	380.666	94	1.058	455.388
45	2.198	382.864	95	1.047	456.435
46	2.151	385.015	96	1.036	457.471
47	2.105	387.120	97	1.026	458.497
48	2.062	389.182	98	1.015	459.512
49	2.020	391.202	99	1.005	460.517
50	1.980	393.183	100	0.995	461.512

Production Schedule

Units of A used for production	Total A+X produced	Minimum A	Units of A used for production	Total A+X produced	Minimum A
1	25.730	0.5	51	80.890	25.5
2	29.982	1	52	81.606	26
3	32.930	1.5	53	82.318	26.5
4	35.291	2	54	83.027	27
5	37.311	2.5	55	83.733	27.5
6	39.103	3	56	84.436	28
7	40.734	3.5	57	85.136	28.5
8	42.242	4	58	85.833	29
9	43.653	4.5	59	86.528	29.5
10	44.987	5	60	87.220	30
11	46.256	5.5	61	87.909	30.5
12	47.472	6	62	88.596	31
13	48.641	6.5	63	89.281	31.5
14	49.770	7	64	89.963	32
15	50.865	7.5	65	90.643	32.5
16	51.928	8	66	91.321	33
17	52.964	8.5	67	91.997	33.5
18	53.975	9	68	92.670	34
19	54.964	9.5	69	93.342	34.5
20	55.933	10	70	94.012	35
21	56.883	10.5	71	94.679	35.5
22	57.817	11	72	95.345	36
23	58.735	11.5	73	96.009	36.5
24	59.639	12	74	96.671	37
25	60.529	12.5	75	97.331	37.5
26	61.407	13	76	97.990	38
27	62.274	13.5	77	98.647	38.5
28	63.130	14	78	99.303	39
29	63.976	14.5	79	99.956	39.5
30	64.813	15	80	100.609	40
31	65.641	15.5	81	101.260	40.5
32	66.460	16	82	101.909	41
33	67.272	16.5	83	102.557	41.5
34	68.076	17	84	103.203	42
35	68.873	17.5	85	103.848	42.5
36	69.663	18	86	104.492	43
37	70.447	18.5	87	105.134	43.5
38	71.224	19	88	105.775	44
39	71.996	19.5	89	106.415	44.5
40	72.763	20	90	107.053	45
41	73.524	20.5	91	107.691	45.5
42	74.280	21	92	108.327	46
43	75.032	21.5	93	108.962	46.5
44	75.778	22	94	109.595	47
45	76.521	22.5	95	110.228	47.5
46	77.259	23	96	110.860	48
47	77.993	23.5	97	111.490	48.5
48	78.722	24	98	112.119	49
49	79.449	24.5	99	112.748	49.5
50	80.171	25	100	113.375	50

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