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Environmental Economics and Policy Studies
The Official Journal of the Society for Environmental Economics and Policy Studies / The Official Journal of the East Asian Association of Environmental and Resource Economics

ISSN 1432-847X

Environ Econ Policy Stud
DOI 10.1007/s10018-015-0107-4

Springer

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RESEARCH ARTICLE

Effects of farmer managed natural regeneration on livelihoods in semi-arid West Africa

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Received: 22 November 2013 / Accepted: 12 February 2015

Abstract This paper used a multivalued treatment framework to assess the effects of farmer managed natural regeneration (FMNR) on selected outcomes among 1080 rural household farmers in the Sahelian and Sudano-Sahelian ecozone of West Africa Sahel. The results indicate that keeping, protecting and managing trees in the farmland have significant effects on the livelihoods of the rural poor in the Sahelian countries. If 1000 households in a community decide to practice the FMNR continuously, it results in an increase in the gross income by US$ 72,000 per year. Noticeable changes are also observed on the value of tree products, with an observed significant increase in the value of the products harvested from tree by about 34–38 % among those actively practicing FMNR as compared to their counterparts. The results also lend support to the household resilience hypothesis of FMNR in that it leads to a significant increase of the dietary diversity by about 12–14 %. However,

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Published online: 01 March 2015

it also appeared that several factors impeded the regeneration of trees on farms. To foster the widespread dissemination and enhance the capacity of farmers to increase, diversify and sustain tree-based production systems, an enabling institutional, technical and policy environment needs to be promoted.

Keywords Agroforestry · FMNR · Livelihoods · Multivalued treatment · Sahel

1 Introduction

The importance of the parkland system in the Sahelian and Sudanian ecozones is well-known as the rural communities in these areas are vulnerable to climate hazards, due to their dependence on natural resources and climate sensitive livelihoods (Batterbury and Warren 2001; Duvall 2007; Tsurumi and Managi 2013). The parklands have at least three main functions in the household economy of rural communities living in or adjacent to them.

Firstly, they help to fulfill households' subsistence and consumption needs in terms of, e.g. energy and nutrition as well as medical and construction purposes. Secondly, they serve as a safety net in times of crises (e.g. income shortages from other income sources, e.g. crop failure) and thirdly, some AFTPs provide regular cash income (Kater et al. 1992; Sabiiti and Cobbina 1992; Hall et al. 1996, 1997; Cavendish 2000; Campbell and Luckert 2002; Maranz et al. 2004; Shackleton and Shackleton 2004; Diallo 2001; Becker and Statz 2003; Teklehaimanot 2004; Kalinganire et al. 2007; Sidibé and Williams 2002; Kouyaté 2005; Cavendish 2002; Angelsen and Wunder 2003; Chileshe 2005; Shackleton et al. 2007; CIFOR 2011).

Added to these provision services, Jonsson et al. (1999) reported agricultural crops under trees were less exposed to excessive temperature of above 40 °C. Trees from agroforestry parklands can also reduce wind speed while increasing soil and air humidity as well as diseases like fungal attacks (Bayala et al. 2014). For soil property, recent studies of Sahelian agroforestry parklands have revealed a decrease in soil bulk density and as a consequence, soil under trees displayed higher porosity compare to adjacent open areas (Sanou et al. 2010 quoted by Bayala et al. 2014). Beyond the above-mentioned provision and regulation services, trees in the parklands provide also supporting services as they contribute to the reduction of carbon in the atmosphere by accumulating biomass via photosynthesis. This process is important as indicated by Bayala et al. (2014), in improving soil properties when accumulated biomass is stored in the below-ground compartment as soil carbon. However, the relationship between parkland trees and soil fertility is not simple and unidirectional because some trees are more likely to regenerate and thrive in spots of higher fertility. Thus, farmer managed natural regeneration can be perceived as an improved land-use management practice that is also essential to reduce greenhouse gases in the atmosphere.

These parklands are the result of conversion of forest to agricultural landscapes. In the process, farmers maintained some tree species that they found useful either for the products or environmental services. If young trees emerge through natural regeneration, and the farmer finds the species useful, then he/she protects and manages that species in the parkland. The practice of actively managing and protecting non-planted trees and shrubs with the goal of increasing the value or quantity of woody vegetation on farmland is known as farmer managed natural regeneration (FMNR) (Abasse et al. 2009; Haglund et al. 2011). Pye-smith (2013) added that FMNR is a practice which involves identifying and protecting the wildlings of trees and shrubs on farmland. It depends on the existence of living roots systems and seeds. Shoots from roots grow more rapidly than saplings from seed, and they make up the bulk of protected woody matter on farm. Farmers will generally choose five of the strongest stumps they wish to retain on their land, pruning away the remainder. These stems can periodically be harvested to provide firewood and timber. For larger trees, farmers will often allow one stem to develop into a full-size tree. The species favored by farmers vary from place to place; so does the density of the trees. Some projects have advised farmers to keep 40 trees/ha, but densities of over 150 are not unusual.

While there are common parkland species throughout the Sahelian/Sudanian ecozones, the composition of species differs across space due to rainfall conditions, topographical location, soils and farmers' preferences for tree species and functions (Faye et al. 2011). Tree density is similarly variable and anthropogenic factors are also important in its determination. The management of trees to protect the soil from drying out and the diversification of agricultural products are additional strategies to cope with climate hazards (Robledo et al. 2012).

Some of the benefits from FMNR have been studied but not well quantified in terms of economics and livelihoods (Haglund et al. 2011). Furthermore, there has been no systematic study of how such benefits vary across the landscape according to the parklands, countries, etc.

The main objective of this study is to provide information about the economic benefits of FMNR practices and other socio-cultural benefits to guide decisions on whether, where and how to scale up the practice to other dryland and sub-humid areas. In achieving this, the paper aims to provide insight into two questions. First, what is the level of economic benefits that communities and households obtain from FMNR? Second, how do these benefits differ among different socio-environmental conditions such as dominant parkland type? Our econometric analysis is based on cross-sectional data collected from a stratified sample of 1080 households residing in four countries (Burkina Faso, Mali, Niger and Senegal). The livelihood benefit variables include crop production (quantity of cereals harvested), household income and food security as captured by the food consumption score (FCS) and coping strategy index (CSI).

The rest of the paper is organized as follows. The next section outlines the theoretical framework used to estimate the impact of FMNR practice on the selected outcomes, and describes the sampling procedure of the study and the type of data used for estimation. The results and discussion section provides basic descriptive statistics and presents the estimated impacts of FMNR practice. The last section summarizes the main findings, draws some policy implications and highlights areas for further research.

2 Data and theoretical framework

2.1 Site selection and data collection

A key factor in the selection of sites was the practice of FMNR techniques by farmers. Whereas the parkland system is ubiquitous in the four countries, evidence for regreening suggests that the phenomenon had been more widespread over recent decades only in certain locations. The study focused on such areas to have a balanced sample of households that practiced FMNR to various degrees and households that did not practice any form of FMNR. The clustered locations of the households surveyed are shown in Fig. 1a–d.

Since the aim is to determine the potential for scaling up of FMNR, it is critical to understand how the types and levels of benefits from existing FMNR differ according to different contexts. The key drivers of productivity of FMNR are rainfall, soils and management whereby the types of species, the growth rates of the vegetation, and the overall potential for vegetation cover is greatest in the more humid Sahelian ecozone. Thus a critical stratification was between the semi-arid and dry sub-humid zones (with 600 mm per year used as the defining threshold). This also enabled the project to select sites within different parkland systems, some of which have a dominance of one or two species and others which are more mixed. Benefits are not only driven by supply side factors but also by the demand side, and market access to urban areas is often a key variable in creating demand for a variety of rural commodities and parkland products and boosting prices for such products. Thus a second critical stratification variable was proximity to major markets, whether they are urban or rural trading centers. Market access was measured by travel time where 2 h was used as a cut off to distinguish between relatively high and relatively low access. Combining the climate and market variables together produces four possible scenarios or strata for site selection: semi-arid climate with low market access, semi-arid climate with high market access, dry sub-humid climate with low market access and dry sub-humid climate with high market access.

Within each of these four strata, two sites were selected for each country (but four sites were chosen in Niger) so that eight sites in all were initially selected (20 households in each site). Additional sites were included in a second round of sampling to correspond to additional FMNR project sites taking place primarily in drier areas.

Altogether, 1080 household surveys were conducted: 480 in Niger, 240 each in Burkina Faso and Mali, and 120 in Senegal. More surveys were conducted in Niger because FMNR had been practiced for a longer period of time in Niger than in the other countries. Therefore, surveys in Niger could better capture the long-term benefits of FMNR.

The formal survey captured basic household information to determine if benefits from FMNR vary due to different contextual factors (climate, market access, pattern of FMNR, management system) and types of households (e.g. female headed households, poorer households, households with smaller farms). The survey collected quantitative information on FMNR found on farm plots, including the type of species, their number and age; costs of establishment and opportunity costs;

sourcing of tree products in non-farm landscapes like collecting fuel wood and fruits in woodlands; and the standard types of production and income variables for households (including quantities of wood and other tree products harvested and sold in 2011–2012; crop production, livestock production and sales; income from other enterprises). Other income generating sources were also enumerated to enable the calculation of household income (including valuation of agricultural production that is consumed by the household). Data on market values of tree products were

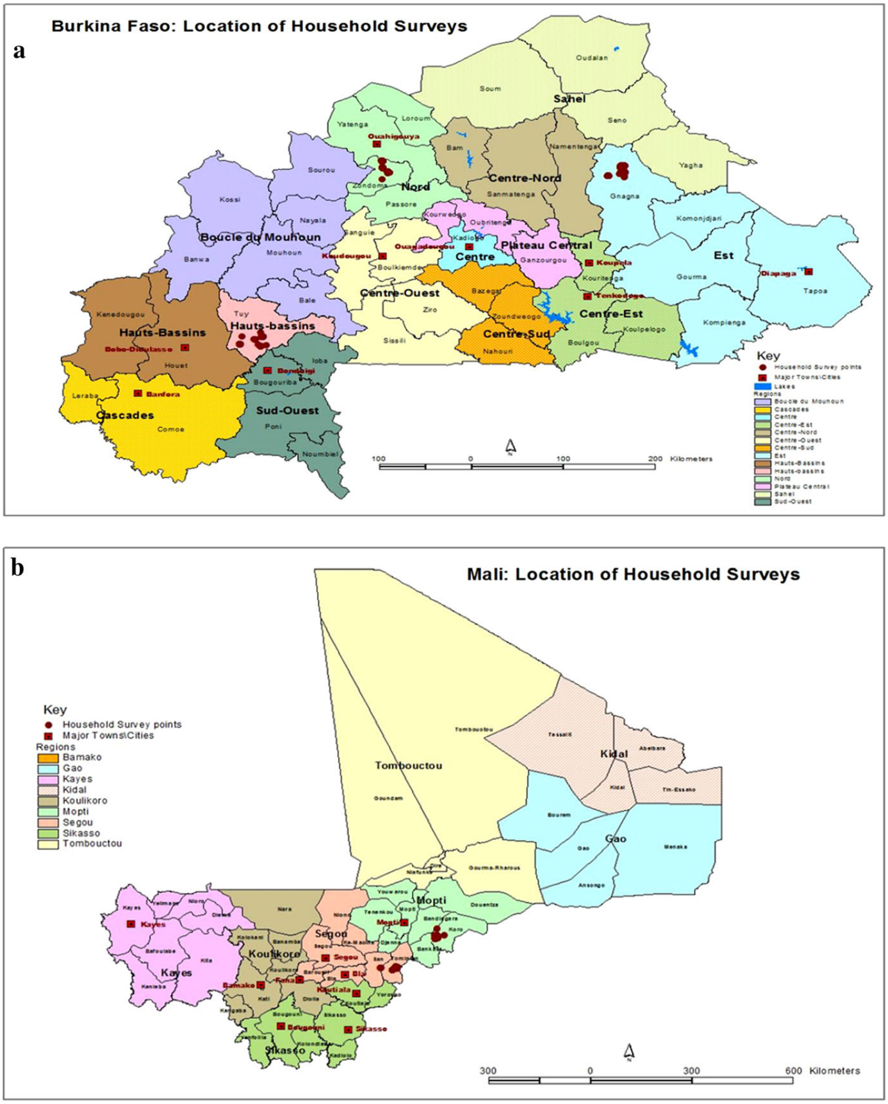

Fig. 1 **a** Location of household surveyed in Burkina Faso. **b** Location of household surveyed in Mali. **c** Location of household surveyed in Niger. **d** Location of household surveyed in Senegal

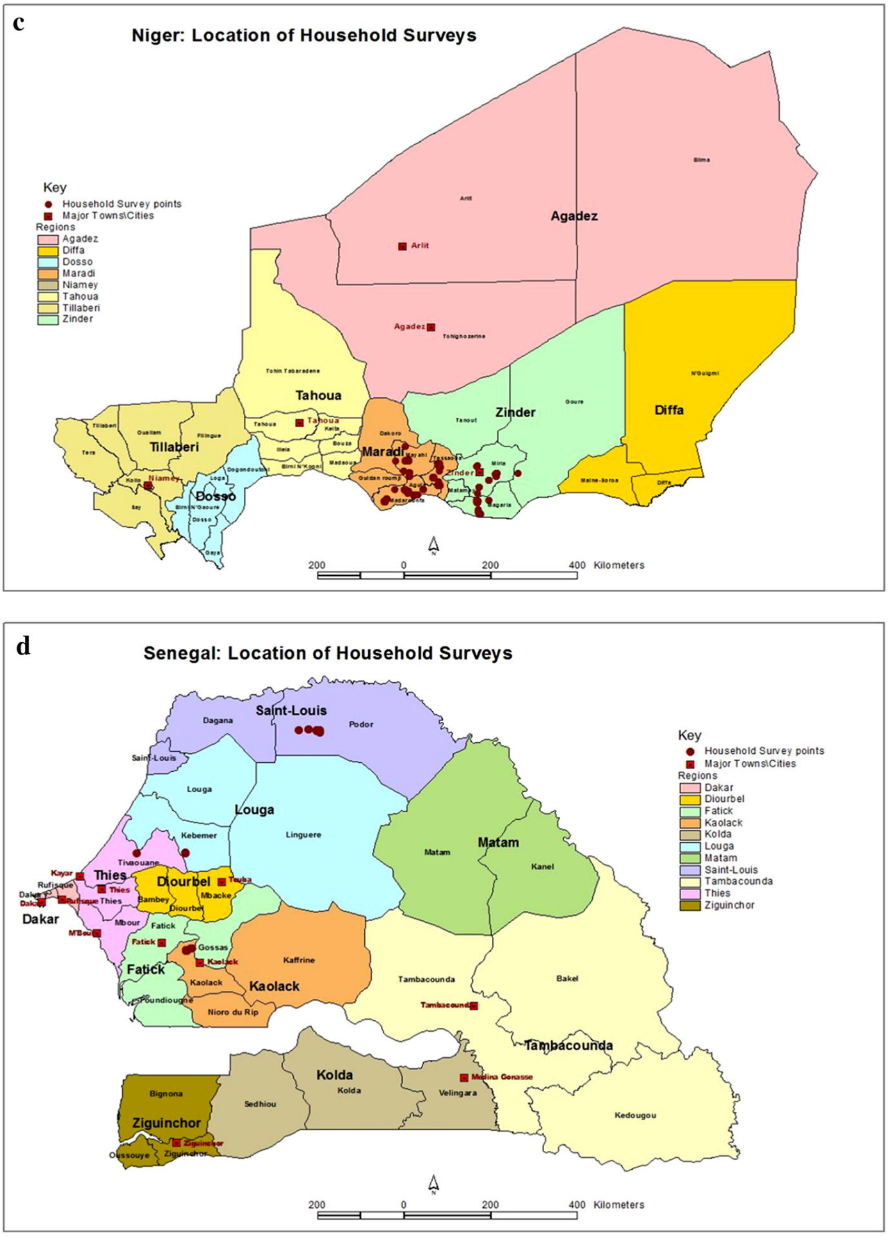

Fig. 1 continued

ascertained from households, and these were complemented by additional market information on prices and unit measures.

Household members were asked qualitative questions to understand their perception of a broad set of benefits, costs, and risks associated with FMNR. Of major interest was whether households perceive FMNR to have any additional environmental services, such as improved soil fertility, improved water management; if the regenerated vegetation is perceived as a buffer against shocks; and whether the integration of FMNR helps to reduce overall risks (e.g. variation of production and income).

2.2 Theoretical framework

In normal observational impact studies involving technology adoption, there is generally a cohort using the technology compared against a control group that did not use the technology. However, FMNR is a complicated technology that does not necessarily fit into the two categories. First, virtually all trees in the Sahel are regenerated naturally and it is not always easy to identify the degree to which the regeneration was facilitated by farmers' practices. Thus, adoption is defined more as a matter of degree of natural regeneration with or without farmer management/ assistance. The species favored by farmers vary from place to place; so does the density of the trees.

On the basis of the data gathered from different households and farmers' plots (for each species, the number of trees by different diameter groups), different cutoff levels for low, medium and high density were used to reflect differences in parkland systems. Based on additional characterization criteria and the score assigned to each of them we came out with a categorization of FMNR in three different groups: low, new/young and continuing/always FMNR.

Based on the field experience and observations, we present in Fig. 2 the decision tree used to categorize farmers according to the intensity of farmer managed natural regeneration practices. At one extreme end are farms where there is low tree density of only old trees, indicating that the farmer is not practicing any FMNR. At the other extreme are farms with high tree density of only young trees, which could reflect active FMNR. Likewise, there is everything in between. Generally speaking, a farmer managed natural regeneration practitioner is someone who: (1) owns at least one farm plot under a given tenure arrangement; (2) has a good or very good knowledge of farmer managed natural regeneration practices by doing certain tree management practices; (3) keeps and manages a big proportion of the dominant tree species found in many parklands within the village. In most cases, those under lease and loan tenure arrangements are less likely motivated to engage themselves in the farmer managed natural regeneration practices.

Based on the decision tree,[1] we observed for instance from the data gathered from the field that, an active farmer practicing FMNR continuously is someone who owns at least one farm plot with abundant density of trees of different sizes (70 ha^{-1} at least on average) equitably distributed within the farm and the species diversity[2] being normal according to the main agroforestry species found in that ecological area (75 % in most cases). By contrast, a farmer practicing FMNR at low levels is

[1] For more details on the decision tree, see the Appendix.

[2] The number of tree species recorded in the different farms owned or managed by a household divided by the maximum number of tree species found in the village.

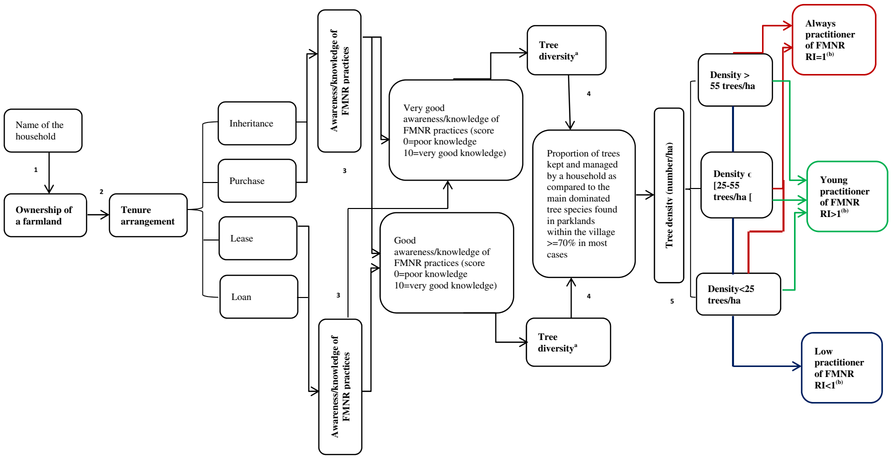

Fig. 2 Decision tree to categorize farmers according to the intensity of farmer managed natural regeneration (FMNR) practices. [b]The regeneration index $\left(\mathrm{RI}_i = \frac{\sum_{j=1}^{2} n_{ij}}{\sum_{j=3}^{5} n_{ij}}\right)$, $i \neq j$; [a]expressed as a percentage of trees kept and managed by a household as compared to the main dominant tree species found in the parklands within the village

one who owns at least one farm plot within which there is a sparse or low number of old trees (15 ha^{-1} maximum on average) as well as small trees (8 ha^{-1} maximum on average) and the species diversity being normal according to the main species found in that ecological area (100 % of old trees in most cases). Finally, a young active farmer practicing FMNR owns at least one farm plot with a somewhat abundant density of young trees (a maximum of 45 ha^{-1} on average), very few old trees (less than 9 ha^{-1} on average); the species diversity being normal according to the ecology of that zone. Table 1 presents the distribution of the different categories of farmers according to FMNR practice in the Sahel.

The main observation stemming from Table 1 is that FMNR as a practice is everywhere in the Sahel and only differs by degree. Just below 30 % of the households practice FMNR at a low level in Sahel with some variation within different countries. At the same time, about 35 % of farmers are either ‘young practitioners’ or ‘always practitioners’ of FMNR.

2.2.1 Average treatment effect of farmer managed natural regeneration (FMNR) practices on selected outcomes

Many disciplines have spawned literature concerned with estimating the effects of treatments, interventions or programs. These methods range from the naive approaches—such as the before and after approaches—to the rigorous econometric or statistical approaches, such as structural econometric modeling approach and potential outcomes approach. We proceed in the context of the potential outcomes framework variously attributed to Quandt (1972) and Rubin (1974) among others.

Table 1 Distribution of farmers according to their farmer managed natural regeneration status (%)

Category	Burkina $N = 240$	Mali $N = 240$	Niger $N = 480$	Senegal $N = 120$	Sahel $N = 1080$
Farmers practicing FMNR at lower level	23	21	30	52	29
Young active farmer practicing FMNR	51	52	25	21	36
Active farmers practicing FMNR	26	27	45	27	35

Imbens (2000) and Lechner (2001) extend this framework to multi-treatment programs. Potential outcomes approach involves the estimation of average treatment effects. The advantage of the potential outcomes approach is that it relaxes some of the stringent assumptions required by the structural econometric modeling approach (Angrist and Imbens 1991; Abadie 2003).

In this paper, we use a framework that is similar to that outlined by Rubin (1974) and described in Angrist and Imbens (1991).We denote individuals by ''i'' and treatment by ''j'' with Y_{ij} signifying the potential outcome for individual ''i'' in treatment ''j''. As a notational convention, capital letters indicate quantities of the population or of members of the population, whereas small letters represent their respective quantities in the sample of size N ($i = 1, \ldots, N$). The units of the sample are supposed to stem from N independent draws in the population. Additionally, we denote variables that are unaffected by treatments called covariates by X. Let $D_{ij} \in \{0, 1\}$ be treatment indicators for each of the $j = 0, \ldots, J$ treatments, where $D_{ij} = 1$ for individual ''i'' receiving treatment ''j'' and $D_{ij} = 0$ otherwise, where of necessity $\sum_{j=0}^{J} D_{ij} = 1$ for all ''i''. The observed outcome then becomes $Y_i = \sum_{j=0}^{J} D_{ij} Y_{ij}$. The causal effect, for example defined as the difference of the two potential outcomes, can never be estimated because the respective counterfactuals (Y_j or Y_0) to the observed outcome (Y_{ij}) are never observed. However, under certain assumptions the average causal effect, denoted by and defined in Eq. (1), is identified.

$$\vartheta_0 = E\big((Y_j - Y_0)|D_j = 1\big) = E\big(Y_j|D = 1\big) - E(Y_0|D = 1). \tag{1}$$

This parameter indicates the mean effect in the population of all units receiving treatment ''j''.

The difficulty with the identification of ϑ_0 from a large random sample is the term $E(Y_0|D = 1)$ because the pair $(y_i^0, d_i = 0)$ is not observable. Much of the literature on causal models in statistics and selectivity models in econometrics is devoted to find identifying assumptions to estimate $E(Y_0|D = 1)$ by somehow using the observable pairs $(y_i^0, d_i = 0)$. One such condition states that the assignment be random conditional on a set of covariates (Rubin 1977). Hence, the assignment is dependent of the potential non-treatment outcome conditional on the value of a covariates set or attributes set (conditional independence assumption, CIA).

$$Y_0 \coprod D|X = x, \forall x \in \chi \quad (2)$$

χ denotes all of the attribute space for which the treatment effect is defined. In a multiple treatment context, Imbens (2000) and Lechner (2001) define a variety of other parameters, such as the mean impact of receiving treatment ''*j*'' relative to treatment ''*k*'' for those who receive treatment ''*j*'' and the mean impact of treatment ''*j*'' on those who receive either treatment ''*j*'' or treatment ''*k*''. Due to the nature of our data, we are going to measure these additional parameters.

Multiple treatments Although the literature on binary treatment variable is well advanced and extensive, the literature on multivalued treatment variables is more recent. Imbens (2000) and Lechner (2001) generalize Rosenbaum and Rubin's (1983) potential outcome approach for the binary treatment variable to the multivalued treatment variable case.

The interest lies in the causal effects of the treatment on some outcome variable, where the treatment of interest, T_i takes integer values between 0 and K. Consider N units which are drawn from a large population. For each individual i, $i = 1, \ldots, N$, in the sample the triple set (Y_i, T_i, X_i) is observed. $D_t(T_i)$ is the indicator of receiving the treatment t for individual i.

$$D_t(T_i) = \begin{cases} 1, & \text{if } T_i = t \\ 0, & \text{otherwise} \end{cases}$$

The vector of characteristics (covariates) for the ith individual is denoted by X_i. For each individual there is a set of potential outcomes $(Y_{i0}, \ldots, Y_{iK})$. Y_{it} denotes the outcome for each individual i, for which $T_i = t$ where $t \in \zeta = \{0, \ldots\ldots, K\}$. Only one of the potential outcomes is observed depending on the treatment status. Adopting the potential outcomes framework pioneered by Rubin (1974), the observed outcome, Y_i, can be written in terms of treatment indicator, $D_t(T_i)$ and the potential outcomes, Y_{it}:

$$Y_i = \sum_{t=0}^{K} D_t(T_i) Y_{it}.$$

Using the potential outcome framework, Lechner (2001) defines several pairwise treatment effects. The first is the average effect of the treatment m relative to treatment l. It measures the mean effect of treatment over the entire population:

$$\tau^{ml} = E[Y_{im} - Y_{il}]$$

The second treatment effect is the expected effect on an individual randomly drawn from the population of participants in treatment m only:

$$\vartheta^{ml} = E[Y_{im} - Y_{il} | T_i = m]$$

The average treatment effects τ^{ml} and τ^{lm} are symmetric, i.e. $\tau^{ml} = -\tau^{lm}$ but $\vartheta^{ml} \neq -\vartheta^{lm}$. ϑ^{ml} measures the effect of the treatment m with respect to treatment l for the subpopulation of individuals who receive the treatment m. On the other hand,

$-\vartheta^{lm}$ measures the treatment effect of m with respect to the l for the subpopulation of individuals who receive the treatment l.

Since only one of the potential outcomes is observed, the above-defined average treatment effects cannot be identified without further assumptions[3] (Imbens 2000; Cattaneo 2010; Wooldridge 2010).

Based on the identification results one can use a regression adjustment technique to estimate $K + 1$ conditional mean functions by parametric regression as in the binary treatment case (Rubin 1977; Hirano and Imbens 2001). Thus, the conditional mean functions of the potential outcomes are specified as follows:

$$E[Y_{it}|X_i] = E[Y_i|T_i = t, X_i] = \beta_{0t} + X_i^{'}\beta_{1t},$$

where $\beta_t = \left[\beta_{0t}\beta_{1t}^{'}\right]^{'}$ is the vector of unknown parameters and β_{1t} has the same dimension as X_i. ing $\hat{\beta}_t$ the treatment effects parameters, τ^{ml} and ϑ^{ml}, can be estimated by the following:

$$\hat{\tau}^{ml} = (\hat{\beta}_{0m} - \hat{\beta}_{0l}) + \frac{1}{N}\sum_{i=1}^{N} X_i^{'}(\hat{\beta}_{1m} - \hat{\beta}_{1l})$$

$$\hat{\vartheta}^{ml} = \left(\hat{\beta}_{0m} - \hat{\beta}_{0l}\right) + \frac{1}{N_m}\sum_{i:D_t(T_i=m)=1}^{N} X_i^{'}\left(\hat{\beta}_{1m} - \hat{\beta}_{1l}\right),$$

N_i is the number of observations who take part in the treatment $T_i = t$. Instead of specifying the $(K + 1)$ regression models, one can define one regression equation depending on the treatment parameter of interest (for more details, see Hirano and Imbens 2001; Wooldridge 2007; Bang and Robins 2005).

In our data, $j = 1$ denotes the low practice *FMNR* treatment, $j = 2$ denotes the new/young practice *FMNR* treatment and $j = 3$ denotes the always/continuous practice *FMNR* treatment.

Matching is unambiguously preferred to standard regression methods for two reasons. First, matching estimators highlight the problem of common support, since treatment effects can only be estimated within the common support. Where there is poor overlap in support between the treated and the non-treated, this raises questions about the robustness of traditional methods relying on functional form to extrapolate outside the common support. Secondly, matching does not require functional form assumptions for the outcome equation (that is, it is non-parametric).

[3] As with any type of estimator, we must make some assumptions to use treatment-effects estimators. The particular assumptions we need for each estimator implemented by the multi valued treatment effect framework and for each effect parameter vary, but some version of each of the following is required: The conditional-independence (CI) assumption restricts the dependence between the treatment model and the potential outcomes. The overlap assumption ensures that each individual could receive any treatment level. The independent and identically distributed (i.i.d.) sampling assumption ensures that the potential outcomes and the treatment status of each individual are unrelated to the potential outcomes and treatment statuses of all other individuals in the population.

Regression methods impose a form on relationships (usually linear) which may or may not be accurate and which propensity score matching (PSM) avoids. However, if there are strong indications about the nature of the functional form for the outcome equation for the population in question, either from theory or from earlier empirical research, there are efficiency gains from imposing it in the estimation. It is also important to bear in mind what PSM can do, but also to note its limitations as an evaluation tool. Its strength lies in estimating mean program effects for a population or sub-group for a binary treatment variable: in other words the PSM cannot handle multivalued treatments.

The multivalued treatments framework proposed in this paper estimate with flexibility potential-outcome means (POMs), average treatment effects (ATEs), and average treatment effects among treated subjects (ATETs) using observational data. Indeed, treatment effects can be estimated using regression adjustment (RA), inverse-probability weights (IPW), and "doubly robust" methods, including inverse-probability-weighted regression adjustment (IPWRA) and augmented inverse-probability weights (AIPW), and via matching on the propensity score or nearest neighbors.

The outcome models can be continuous, binary, count, or non-negative. Continuous outcomes can be modeled using linear regression; binary outcomes can be modeled using logit, probit, or heteroskedastic probit regression; and count and non-negative outcomes can be modeled using Poisson regression. Multivalued treatments are modeled using ordered or multinomial logit regression (StataCorp 2013).

The analytical support used in this study implements two doubly robust estimators, the AIPW estimator and the IPWRA estimator. Doubly robust estimators combine the outcome modeling strategy of RA and the treatment modeling strategy of IPW. These estimators have a remarkable property: although they require us to build two models, we only need to specify one of the two models correctly to obtain correct estimates of the treatment effect (Cattaneo et al. 2013).

3 Results and discussion

3.1 Socio-economic characteristics

Table 2 presents summary statistics for the sampled households. The average number of household members between 16 and 59-year old ranged from 3 in Burkina Faso to 9 in Mali. Average household size was about 12 persons, with a range of 8–16 persons per household. Household size was smaller in Burkina Faso, compared with the other countries. Between 93 and 100 % of the households interviewed, depending on the country, were headed by males. About 14 % of the households have at least one adult with primary school education, while 65 % of the household heads have not completed formal primary education and only 7 % have someone with secondary school education.

Production of annual crops and livestock are the main sources of income for the majority of the households in the four countries. Likewise, sale of agroforestry tree

Table 2 Socio-economic characteristics of the sampled households

Variables	Countries			
	Burkina Faso ($N = 240$)	Mali ($N = 240$)	Niger ($N = 480$)	Senegal ($N = 120$)
Household characteristics				
Gender of hh head (% of male)	92.9	100	99	97.5
Number of male aged 16–59	1 (1.0)	5 (5.1)	2 (1.3)	3 (1.6)
Number of female aged 16–59	2 (1.6)	4 (3.4)	2 (1.5)	3 (2.0)
Household size	8 (4.0)	16 (10.0)	12 (6.0)	12 (6.0)
Education if hh head (formal education)				
None (% hh)	76.7	85.8	32.4	66.67
Medersa (% hh)	2.1	0.9	47.6	–
Primary (% hh)	16.3	12.4	15.2	16.13
Secondary (% hh)	5.0	0.9	4.8	16.13
Post-secondary (% hh)	–	–	–	1.08
Income sources				
Crop (% hh)	32.92	71.7	58.33	31.67
Livestock (% hh)	37.08	57.4	12.06	24.17
Off-farm (%hh)	17.50	62.08	51.67	48.33
Agroforestry (% hh)	45.42	50.83	18.75	48.33
Total hh income ($US)	252.7 (198.03)	262.09 (184.03)	176.2 (146.9)	640.78 (386.6)
% agroforestry income	23.8	10.1	10.0	7.4
% livestock income	6.3	20.4	4.6	7.9
% crop income	64.2	62.6	69.3	83.6
Farm characteristics				
Farm size (ha)	5.96 (5.53)	9.09 (9.05)	2.17 (1.9)	8.3 (5.8)
Average yield kg ha^{-1} of the main crops				
Millet	634	597	318	438
Sorghum	764	–	–	–
Maize	1615	–	393	–
Land acquisition				
Inheritance (% hh)	85.86	96	90	84.75
Sharecropping (% hh)	1.78	0.97	–	–
Lend (% hh)	4.12	2.18	1	11.86
Buy	3.65	–	8	–
Gift	–	0.44	1	3.39
Water harvesting and soil fertility management				
Soil and water management				
Drilling (% hh)	–	2.5	0.21	0.83
Rainwater harvesting (% hh)	–	2.08	–	3.3
Irrigation (% hh)	–	1.25	–	–
Improved planting pits (zai)	38	7.5	–	–

Table 2 continued

Variables	Countries			
	Burkina Faso ($N = 240$)	Mali ($N = 240$)	Niger ($N = 480$)	Senegal ($N = 120$)
Contour stone bunds	63	8.33	–	–
Soil fertility management (% of hh)				
Proportion of plots with fertilized trees: *faidherbia*	23	46	58	92
Proportion of plots with fertilizer trees other than *faidherbia*	82	94	92	56
Use of fertilizer	63	26	26.5	9.7
Use of compost	30	56.7	15.4	13.3
Use of manure	75	92.08	62.5	90.8
Use of leaves from trees	4	82.5	73.8	26.7

hh household

Values in parenthesis are standard errors

products, particularly fuelwood, fodder and fruits, is another important source of income for the majority of the households (although households sell only a small fraction of the tree products that they harvest). The mixed crop–tree–livestock farming system notwithstanding, crop production accounts for over 60 % of the total household income in all the countries as shown in Table 2.

The average land size is estimated at 6.4 hectares per household, although the average size ranges from 2.2 ha in Niger, to 9.1 ha in Mali. The estimated average landholding size is slightly higher than expected in some countries. The larger size could be due to the sampling method used in this study. It may be that villages where FMNR has become popular could have slightly larger landholdings than those that were not targeted by programs for upscaling of FMNR.

In the case of Niger, the crop fields were dominated by millet as the main crop, but a large number was also intercropped with sorghum. Rainfall was lower than in recent years and this might explain rather low yields found. The use of fertilizer is low both in percentage of plots and mean amount applied. Manure is much more commonly used by farmers and the amount of nearly 1500 kg per hectare suggests a nitrogen application of around 20–25 kg per hectare according to studies from Niger (Powell and Williams 1993).

Inorganic fertilizer is not used much by farmers and thus is not an alternative to using manure which is common or fertilizer trees which are found on almost all plots. An important finding is that manure and inorganic fertilizer use per hectare is significantly linked to the density of mature fertilizer trees on the same plot, the correlations being between $r = 0.16$ and 0.19. This supports the argument that farmers are intensifying input use where there are relevant agroforestry practices.

In the Mali sites of Bankass and Tominian, the most dominant cereal crop was millet. There were just a few dozen cases where sorghum or fonio was the main crop. Compared to Niger, millet yield is noticeably higher (Table 2). Fertilizer use is about the same as in Niger, which is rare and in small quantity. Manure use is less frequently found on plots in Mali compared to Niger, though the mean amount is higher in Mali, when it is used.

The strongest tree-input correlations are with *F. albida* and it is mainly between manure use ($r = 0.2$ with old and 0.13 with young *F. albida* trees). So there is some evidences, as in the case with Niger, that farmers aim to apply more nutrient inputs on fields where soil fertility trees are present (in this case *F. albida* mainly).

Contrary to the situation in Niger and Mali, millet is not so dominant a crop in the study sites of Burkina Faso. In fact, millet, sorghum and maize are equally represented in the sample each being the main crop on about 30 % of cereal plots. The distribution differs by location, with maize found more often in the western sites, millet to the north and sorghum in the north and east. These are considerably different compared to Niger or Mali. Fertilizer use is much more common in Burkina Faso and the doses are also higher. Similarly, the amounts of manure applied are higher than in Mali or Niger. This is attributable in part to the inclusion of a more humid western site where maize is common. Farmers apply more inputs to maize than they do to the other crops. The prevalence of *F. albida* is low and although there are other fertilizer trees found in the fields, the number of mature ones is also modest. Larger fertilizer trees are moderately correlated with manure use per ha (between 0.2 and 0.4).

As for the main crops found in the sample from Senegal, plots are dominated by millet, though there are many types of intercrops found in the millet plots. Again, the case of Senegal represents a slightly different situation as compared to the other countries. Millet yields are between those of Niger and Mali. A likely reason for the somewhat low yields is the extremely low use of inputs, notably the percent of fertilizer use and the amount of manure use, which are the lowest among the countries.

As is common in other countries, there are large numbers of relatively small fertilizer trees but not large numbers of more mature ones. *F. albida* is not strongly correlated with inputs, but together with other older fertilizer trees, they have a modest correlation with fertilizer use (0.11). Manure use is not associated with trees.

On the whole, the results are mixed for water and soil management practices. While in Burkina Faso and Mali, farmers report using both water and soil conservation management practices and soil fertility practices, in Niger and Senegal, the practices commonly used are those related to soil fertility management. In many of these countries the use of compost and manure, as well as fallen leaves appears to be one of the most important techniques used by the farmers to improve the fertility of their farm.

Households in the four countries rely on crop production for income and food. As such, crop production appeared as the most important income generating activity compared with other sources of income such as livestock production, agroforestry and off-farm income sources. However, agroforestry products supplement the farm households' income and food needs, especially during lean periods of the late dry season and early rainy season when crops have not been harvested. Consequently, tree products are the second most important income generating activity after crop production. On the other hand, livestock production, although recognized by farmers as a source of income, still trails crop and tree products.

The conditional independence assumption (CIA), also known as confoundedness and selection-on-observables in the literature, is satisfied if the vector of covariates includes all of the variables that affect both participation and outcomes. Conditional independence is a strong assumption and is not a directly testable criterion; it depends on specific features of the program itself (Cattaneo et al. 2013). Having a rich set of preprogram data helps support the conditional independence assumption by allowing one to control for as many observed characteristics as might be affecting program participation (assuming unobserved selection is limited) (Shahidur et al. 2010). In other words, the CIA requires that a farmers' decision to practice natural regeneration is unrelated to what their outcome would have been in the absence of farmer FMNR.

As a first step in selecting covariates, the correlation coefficient for farmer/household and village attributes and each of the treatment and outcome variables were calculated. From this list, a number of variables were identified as having higher correlation for both treatment and outcomes relative to the other variables. These were also substantiated by the economic theory and previous research in building up the model (Haglund et al. 2011). These included: (1) the number of individuals active in the household, (2) the number of livestock owned by the households evaluated in terms of tropical livestock units (TLU), (3) the proportion of educated members within the household, (4) the total farm size in hectares, (5) if household earns off-farm income, (6) number of contacts with extension agents and, (7) participation in agricultural development project. The summary of variables used in the treatment models is reported in Table 3.

3.2 Impact of FMNR on selected outcomes

The estimated treatment effect parameters are summarized in Tables 4, 5, 6 and 7. We consider different pairwise comparisons for the three FMNR categories. The reported numbers are gains/losses in selected outcomes due to treatments m relative to treatment l. Average treatment of m relative to l is estimated for three groups: (a) for the entire population ($\hat{\tau}^{ml}$ in Table 4); for the subpopulation $T_i = m$ ($-\hat{\vartheta}^{ml}$ in Tables 5, 6); for the subpopulation $T_i = l$ ($\hat{\vartheta}^{ml}$ in Table 7).

The results reveal that in most cases, the estimated mean average effects on the gross income per individual increase as the FMNR status changes from the low level to the new/young level and from the low level to the continuous level (Table 4). The estimated average treatment effect of moving from low practice level of natural regeneration to young level is \$2.5 (10^\$0.39) per individual in Burkina Faso or \$20 for an average household with eight members. The same results indicate that the estimated average effect of moving from low level to the status of continuous practitioner of natural regeneration in Burkina Faso will result in an increase in the total income by \$3 per individual, or \$24 for an average household with eight members. The same calculation can be made for Mali and Senegal.

However, the most significant effects of changing status in the practice of natural regeneration can be observed in Niger (and for the Sahel region as a whole since Niger has the largest sample of households). In other words, an average a household

Table 3 Summary of variables used in the analysis

Variable description	Countries			
	Burkina Faso ($N = 240$)	Mali ($N = 240$)	Rep. of Niger ($N = 480$)	Senegal ($N = 120$)
Household structure				
Percentage of male headed households	70.81	100	99.58	97.50
Number of active members in the household	3 (1.72)	9 (4.8)	4 (1.5)	6 (2.0)
Dependency ratio	0.55 (0.21)	0.48 (0.22)	0.60 (0.14)	0.53 (0.15)
Household size	8 (4.0)	16 (10.0)	12 (6.0)	12 (6.0)
Household endowment				
Production assets				
Size of arable land (ha)	5.96 (5.53)	9.09 (9.05)	2.17 (1.9)	8.3 (5.8)
Number of livestock unit owned	10.48 (12.10)	17.2 (22.6)	9.9 (5.01)	5.34 (5.05)
Transportation assets				
If the household owns a chart (1 = yes)	29.2	92.1	43.5	64.2
If the household owns a motorcycle/bicycle (1 = yes)	17.5	62.5	31.7	4.2
If the household receives off-farm income	17.5	62.08	51.67	48.33
Information assets				
If the household owns a TV (1 = yes)	56.7	18.3	1.5	27.5
If the household owns a cell phone (1 = yes)	61.3	71.7	25.2	54.2
If the highest level of education of the household head is primary (1 = yes)	84.5	74.5	10.04	79.2
If the highest level of education of the household head is secondary (1 = yes)	50	38.3	66.7	61.7
Institutional factors				
Average distance from the main markets (km)	20.07 (20.03)	5.3 (3.7)	7.4 (5.6)	7.1 (5.3)
Number of interactions with extension agents	2.11 (1.8)	0.85 (1.6)	0.33 (0.78)	0.33 (0.92)
If participating in other development projects (1 = yes)	61.7	20.0	22.7	21.7
If membership of farmer organization (1 = yes)	57.08	35.78	18.33	15.13
If the village has a local convention regulating land/resources access and use (1 = yes)	33.33	75.00	16.46	16.67
If has access to credit (1 = yes)	69.58	23.85	19.46	35.00

Values in parenthesis are standard errors

Table 4 Estimated treatment parameters on selected outcomes: average effect of *m* relative to *l*

m	*l*	Burkina Faso $\hat{\tau}^{ml\,a}$	Mali $\hat{\tau}^{ml}$	Niger $\hat{\tau}^{ml}$	Senegal $\hat{\tau}^{ml}$	Sahel $\hat{\tau}^{ml}$
Total income per capita (log $US)						
New/young practitioners	Low practitioners	0.39 (0.38)	0.40 (0.37)	0.59 (0.28)**	0.42 (0.38)	0.69(0.33)**
Always/continuous practitioners	Low practitioners	0.40 (0.41)	0.35 (0.40)	0.76 (0.36)**	0.39 (0.35)	0.82 (0.35)**
Total value of harvested tree products (log $US ha^{-1})						
New/young practitioners	Low practitioners	0.08 (0.19)	0.20 (0.16)	0.12 (0.19)	0.11 (0.17)	0.18 (0.18)
Always/continuous practitioners	Low practitioners	0.64 (0.21)***	0.66 (0.21)***	0.75 (0.21)***	0.64 (0.20)***	0.71 (0.20)***
Total production harvested (t ha^{-1})						
New/young practitioners	Low practitioners	0.25 (0.19)	0.33 (0.18)*	0.33 (0.19)	0.40 (0.19)**	0.44 (0.19)**
Always/continuous practitioners	Low practitioners	0.06 (0.21)	0.16 (0.21)	0.05 (0.20)	0.07 (0.21)	0.19 (0.20)
Food consumption score (log score)						
New/young practitioners	Low practitioners	0.38 (0.16)**	0.35 (0.17)**	0.29 (0.16)*	0.36 (0.16)**	0.34 (0.16)**
Always/continuous practitioners	Low practitioners	0.26 (0.17)	0.24 (0.16)	0.18 (0.17)	0.25 (0.17)	0.24 (0.17)
Number of month with food deficit (log number of months)						
New/young practitioners	Low practitioners	−0.001 (0.10)	0.008 (0.11)	−0.007 (0.12)	0.008 (0.11)	0.03 (0.10)
Always/continuous practitioners	Low practitioners	0.00 (0.12)	0.03 (0.13)	0.02 (0.14)	0.03 (0.14)	0.00 (0.13)

* $P < 10$ %, ** $P < 5$ %, *** $P < 1$ %

[a] Variables in parenthesis are Robust Standard Errors

Table 5 Percentage changes in effects of FMNR on selected outcomes: average changes of m relative to l

m	l	Burkina Faso $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Mali $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Niger $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Senegal $-\hat{\vartheta}^{ml}$ (Robust Std Err.)	Sahel $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)
Total income per capita (log $US)						
Low practitioner	New/young practitioner	0.063 (0.065)	0.067 (0.064)	0.064 (0.065)	0.068 (0.064)	0.097 (0.051)*
Low practitioner	Always/continuous practitioner	0.064 (0.070)	0.059 (0.069)	0.060 (0.070)	0.065 (0.070)	0.129 (0.067)*
Total value of harvested tree products (log $US ha^{-1})						
Low practitioner	New/young practitioner	0.046 (0.109)	0.064 (0.110)	0.066 (0.109)	0.319 (0.130)**	0.103 (0.114)
Low practitioner	Always/continuous practitioner	0.356 (0.141)**	0.376 (0.145)***	0.361 (0.142)**	–	0.335 (0.139)**
Total production harvested (t ha^{-1})						
Low practitioner	New/young practitioner	0.039 (0.031)	0.051 (0.030)*	0.045 (0.026)*	0.048 (0.031)	0.070 (0.032)**
Low practitioner	Always/continuous practitioner	0.009 (0.033)	0.025 (0.034)	0.011 (0.031)	0.022 (0.033)	0.031 (0.034)
Food consumption score (log score)						
Low practitioner	New/young practitioner	0.137 (0.066)**	0.127 (0.068)*	0.102 (0.062)*	0.129 (0.065)*	0.122 (0.067)*
Low practitioner	Always/continuous practitioner	0.096 (0.065)	0.087 (0.067)	0.064 (0.061)	0.089 (0.064)	0.088 (0.068)
Number of month with food deficit (log number of months)						
Low practitioner	New/young practitioner	−0.004 (0.065)	0.005 (0.071)	−0.004 (0.070)	0.005 (0.066)	0.016 (0.068)
Low practitioner	Always/continuous practitioner	0.002 (0.077)	0.019 (0.083)	0.018 (0.085)	0.020 (0.083)	0.003 (0.081)

* $P < 10$ %, ** $P < 5$ %, *** $P < 1$ %

Table 6 Estimated average treatment effects on selected outcomes as percentages of that expected from the young practitioners

m	*l*	Burkina Faso $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Mali $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Niger $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Senegal $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Sahel $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)
Total income per capita (log $US)						
New/young practitioner	Always/continuous practitioner	0.071 (0.057)	0.067 (0.058)	0.066 (0.058)	0.066 (0.067)	0.105 (0.055)*
Total value of harvested tree products (log $US ha^{-1})						
New/young practitioner	Always/continuous practitioner	0.310 (0.129)**	0.324 (0.130)**	0.319 (0.128)**	0.319 (0.130)**	0.240 (0.107)**
Total production harvested (t ha^{-1})						
New/young practitioner	Always/continuous practitioner	−0.003 (0.028)	−0.000 (0.027)	0.000 (0.028)	−0.001 (0.027)	−0.004 (0.027)
Food consumption score (log score)						
New/young practitioner	Always/continuous practitioner	−0.025 (0.023)	−0.021 (0.024)	−0.020 (0.023)	−0.027 (0.024)	−0.003 (0.022)
Number of month with food deficit (log number of months)						
New/young practitioner	Always/continuous practitioner	−0.026 (0.047)	−0.023 (0.049)	−0.040 (0.051)	−0.019 (0.053)	−0.017 (0.049)

* $P < 10$ %, ** $P < 5$ %, *** $P < 1$ %

Table 7 Results of the contrast average treatment effects of FMNR on selected outcomes: average effect of m relative to l

l	m	Burkina Faso $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Mali $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Niger $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Senegal $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)	Sahel $-\hat{\vartheta}^{ml}$ (Robust Std. Err.)
Total income per capita (log $US)						
New/young practitioner	Low practitioner	0.57 (0.32)*	0.43 (0.38)	0.51 (0.37)	0.41 (0.38)	0.44 (0.47)
Always/continuous practitioner	New/young practitioner	0.23 (0.34)	0.064 (0.35)	0.01 (0.39)	0.032 (0.26)	0.05 (038)
Total value of harvested tree products (log $US ha^{-1})						
New/young practitioner	Low practitioner	0.071 (0.192)	0.098 (0.195)	0.112 (0.192)	0.087 (0.194)	0.176 (0.197)
Always/continuous practitioner	New/young practitioner	0.505 (0.167)***	0.527 (0.173)***	0.503 (0.174)***	0.493 (0.162)***	0.567 (0.210)***
Total production harvested (t ha^{-1})						
New/young practitioner	Low practitioner	0.260 (0.195)	0.342 (0.190)**	0.307 (0.182)*	0.305 (0.192)	0.429 (0.194)**
Always/continuous practitioner	New/young practitioner	−0.157 (0.177)	−0.115 (0.185)	−0.165 (0.181)	−0.121 (0.179)	−0.213 (0.187)
Food consumption score (log score)						
New/young practitioner	Low practitioner	0.352 (0.152)**	0.317 (0.162)**	0.276 (0.159)*	0.339 (0.153)**	0.316 (0.158)**
Always/continuous practitioner	New/young practitioner	−0.128 (0.077)	−0.127 (0.076)	−0.127 (0.079)	−0.125 (0.075)	−0.089 (0.076)
Number of month with food deficit (log number of months)						
New/young practitioner	Low practitioner					
Always/continuous practitioner	New/young practitioner	0.007 (0.118)	0.023 (0.116)	−0.001 (0.156)	0.025 (0.117)	−0.014 (0.119)

* $P < 10$ %, ** $P < 5$ %, *** $P < 1$ %

with 12 members will benefit from an increase in gross income by \$48 (10^\$0.59 × 12) and \$72 (10^\$0.76 × 12) for moving from the low to young practitioner status and from the low to continuous practitioner status, respectively. This means that if a community in the study area with 1000 average households newly involved in natural regeneration was to decide to practice continuously natural regeneration, this will result in an increase in gross income in the community by \$72,000, indicating that practicing farmer managed natural regeneration could be an avenue for the development of the rural economy in the Sahelian and Sudano-Sahelian countries of West Africa.[4]

Tree fruits and other edible tree products constitute an important source of income, micronutrients and vitamins that complement needs of the Sahelian population and mainly the marginalized groups. On the basis of the household survey, the quantity of tree products harvested and sold was found to vary from one category of farmers managing natural regeneration to other. The results are strong and significant for all countries indicating that moving from the status of low practitioner to the continuous level has a significant and positive effect on the value of tree products.

The average treatment effect of moving to low FMNR status to the continuous status is \$4 ha^{-1} per individual in Burkina Faso, \$5 in Mali, \$6.3 in Niger, \$4 in Senegal and \$5 in the Sahel as a whole.

In other words, if the 1000 average low practitioners of natural regeneration with a family of eight members were to decide to adopt continuously the technology, this will result in an increase in value of tree products by \$32,000 (1000 × \$4 × 8) in Burkina Faso; \$60,000 (\$5 × 12 × 1000) in Mali for an average farmer with a family of 12 members; \$76,000 (\$6.3 × 1000 × 12) in Niger. The same calculation can be made for Senegal and Sahel as the whole.

In fact, there is much less dispute from scientific point of view about the tangible benefits of FMNR when it comes to providing fuelwood and other materials. During the first year of practicing natural regeneration, farmers will obtain fuelwood from pruned branches, from the second year onwards; the branches will be large enough to sell. One study mentioned by Pye-Smith (2013) found that over 12-year period the wood sold as a result of FMNR in 100 villages in the Niger republic was worth US\$ 600/village/year. Several species found in farmers' fields including *Strychnos spinosa*, *Balanites aegyptiaca*, *Ziziphus mauritiana*, *Adensonia digitata* and *Vitellaria paradoxa* provide edible leaves and fruits for human consumption. These are particularly important during drought, especially for poorer members of the community. A recent study conducted in southern Zinder in Niger found that the sale of leaves from a mature *Adansonia digitata* tree can generate US\$27–US\$75, depending on the spatial and temporal location of the market (Chris 2012).

Cereals and vegetables are the most common staple crops associated with trees in the Sahel. This study also tried to assess the impact of FMNR on crop production. The results indicate that the average treatment effects of going from low practitioner status to new/young practitioner vary from 0.039 to 0.070 t ha^{-1}: with significantly

[4] The linear scaling up method is valid at least in the Niger case because the data are based on a practice that is newly spread on millions of hectares.

different effects in Mali, Senegal and the Sahel globally. Even if there is a positive effect between low and continuous FMNR groups, no significant difference was found between the two groups indicating that the effects of trees on crop production might be affected by both the density and quality of tree species. These results are in line with what is found in the literature. In fact, past studies on tree–crop interactions have clearly shown that trees have highly varying effects on the associated crops when comparing the yield of associated crops in the influence zone of trees with that of a treeless monoculture control plot. Cereal grain yield difference was found to be varying from -0.54 t ha^{-1} under *Balanites aegyptiaca* to $+0.24$ t ha^{-1} under *Faidherbia albida* and biomass yield difference from -1.31 t ha^{-1} under *Parkia biglobosa* to $+4.07$ t ha^{-1} under *Prosopis Africana* (Bayala et al. 2012, 2014).

Most definitions of food security vary around that proposed by the World Bank (2010) and summed up by Maxwell and Frankenberger as "secure access at all times to sufficient food for a healthy life" (Maxwell 1996).

In an emergency food security assessment (EFSA), three key sets of indicators are used to estimate the dimensions of the food security problem (WFP 2009):

- Mortality rates give an indication of risks at the population level.
- Nutrition indicators are used to estimate nutrition status at the individual level.
- Food security indicators focus on assessing access to food and food consumption at the household level.

In our analysis, we employ two categories of food consumption indicators, a FCS and the number of months with food deficit. Food consumption indicators are designed to reflect the quantity and/or quality of people's diets. The most commonly used food consumption indicator is the FCS that represents the dietary diversity, energy and macro and micro (content) value of the food that people eat. It is based on dietary diversity—the number of food groups a household consumes over a reference period; food frequency—the number of days on which a particular food group is consumed over a reference period, usually measured in days; and the relative nutritional importance of different food groups. The FCS is calculated from the types of foods and the frequencies with which they are consumed during a seven-day period.

Each item is given a score of 0–7, depending on the number of days on which it was consumed. For example:

- if potatoes were eaten on three of the last 7 days, they are given a frequency score of 3;
- if potatoes were eaten on three of the last 7 days, even if they were eaten twice on each of those days, at two meals, they are still given a frequency score of 3.

In the analysis, food items were listed according to food groups and the frequencies of all the food items surveyed in each food group were summed. Any summed food group frequency value over 7 was recoded as 7. Each food group is assigned a weight reflecting its nutrient density. For example:

- Beans, peas, groundnuts and cashew nuts are given a weight of 3, reflecting the high protein content of beans and peas and the high fat content of nuts;
- Sugar is given a weight of 0.5, reflecting its absence of micronutrients and the fact that it is usually eaten in relatively small quantities.

The household FCS was calculated for each household by multiplying each food group frequency by each food group weight, and then summing these scores into one composite score.

Solving the problem of food and nutritional security requires a range of interconnected agricultural approaches, including improvements in the productivity of staple crops, the bio-fortification of staple foods, and the cultivation and/or management of a wider variety of edible trees that provide fruits, nuts and vegetables for more diverse diets (Frison et al. 2011). As such, exotic and indigenous fruits cultivated and managed in agroforestry systems are important in Sahelian countries. As well as directly providing edible products, trees in agroforestry systems support food production by giving shade and support to nutritious vegetable crops (Maliki et al. 2012; Susila et al. 2012). Many tree species also assist staple crops through soil fertility improvement. This was demonstrated in an analysis of more than 90 peer-reviewed studies on the planting of nitrogen-fixing green fertilizers, including trees and shrubs, which found consistent evidence of benefits to cereals in semi-arid countries, although the level of response varied by soil type and the technology used (Sileshi et al. 2008; Bayala et al. 2013).

The average effects on FCS of moving from the low to young FMNR status are also positive and significant for all countries in the Sahel given the important complementary role fruits and other edible tree products play as source of micronutrients and vitamins to the cereal-based diet of many Sahelian countries (Sidibé and Williams 2002; Cavendish 2002; Angelsen and Wunder 2003; Chileshe 2005; Kouyaté 2005; Shackleton et al. 2007; Bayala et al. 2013). Though there is no significant effect on the number of months with food deficit, the results show that the communities of farmers practicing natural regeneration at different levels are more resilient during periods of food shortages and scarcity as one of the coping strategy used by those farmers during most periods of scarcity is among others the gathering of food, exploitation of woods for fuel and sale from agroforestry parklands (Sendzimir et al. 2011).

3.2.1 Expressing the average treatment effects (ATEs) as a percentage change

As in the binary treatment case, expressing the ATEs as percentages of the potential outcome measure for the control level often aids interpretation (Table 5). In this paper, we first use the replay facility of the (*teffects aipw command*) of *stata13* to generate those percentages. As indicated in the results reported in Table 5, moving from low to young FMNR status increases gross income by 10 % in the Sahel. Similarly, if an average low Sahelian practitioner of FMNR were to decide to become a continuous manager of natural regeneration, this would result in an increase in gross income by about 13 %.

Noticeable changes can also be observed on the value of tree products. According to the results, if an average low practitioner of FMNR were to become a continuous practitioner, this would result in a significant increase in the value of the products harvested from trees by about 36 % in Burkina Faso, 38 % in Mali, 36 % in Niger and 34 % in the Sahel as a whole.

The positive effect of FMNR on food security is not surprising as similar findings have been reported in the past literature on the role of agroforestry parklands on household resilience (Viet Quang and Nam Anh 2006; Cocks et al. 2008; Reij et al. 2009; Bayala et al. 2013). The results from this study suggest that if an average low farmer managing natural regeneration were to become a young manager of natural regeneration, this would result in a significant increase in the dietary diversity (as captured through the food consumption score) by about 14 % in Burkina Faso, 13 % in Mali, 10 % in Niger, 13 % in Senegal and 12 % in the Sahel globally.

Table 6 provides the average effects of continuously managing natural regeneration as a percentage of the expected new/young management of natural regeneration. Again, the most noticeable results appear to be on tree products. In other words, being a continuous practitioner of FMNR is expected to increase a farmer's value from tree products by 31 % in Burkina Faso; 32 % in Mali, Niger and Senegal; and, 24 % in the Sahel globally relative to a young practitioner of FMNR. These results are in line with the previous findings in the literature. Besides providing essential nutrients and minerals to rural diets, some of these trees are also harvested for medicine, fuel, and other non-edible products and for the raw materials for processed goods (Havinga et al. 2010; Leach et al. 2011). Often, these species provide opportunities to marginalized members of the community, such as women and the poor, as the example of Shea shows (Gustad et al. 2004; Masters 2014).

In the previous cases, we obtained two ATEs, and they were all expressed relative to the base level of low level of FMNR. However, we also try to express the gains to a young practitioner level relative to low level, the gain to a continuous practice level relative to a young level as indicated in Table 7.

The results indicate that moving from the young practitioner of FMNR status to a continuous FMNR status has much larger effects than moving from the low FMNR status to the young FMNR status in terms of tree products. This supports the idea that the practice of natural regeneration must be addressed as a dynamic process if the farmers have to earn more benefits from it. Consequently, farmers must endeavor to continuously apply the practice in the Sahel. By contrast, in terms of crop productivity and food security, it appears that moving from low level to young level of management of natural regeneration significantly provides more benefits in terms of food production and food consumption score. These results are relevant as those indicators can be easily observed more quickly than results based on tree products.

4 Conclusion and recommendations

This study has explored the issues of economic benefits of FMNR practice on the livelihoods of rural households in the Sahelian and Sudano-Sahelian countries of

West Africa. Because FMNR is a complicated technology to observe, the normal observational assessment studies used hitherto to compare a cohort using the technology against a control group that did not use the technology have found difficulties to adequately quantify its benefits in terms of economics and livelihoods in Sahelian countries. Consequently, to better quantify the effects of FMNR on the livelihoods of rural households, the study suggested four aspects or criteria that are related to two dimensions: how farmers are aware of natural regeneration (awareness–knowledge continuum: awareness of FMNR and the diversity of the species managed in the farmland as compared to the main species found in the area) and how they comply in managing natural regeneration (compliance continuum: ownership of at least one farmland and the number and size of trees kept and managed in the farm). The use of these criteria led to the definition of different farmer profiles related to the practice of FMNR.

The multivalued treatment framework analysis was used to assess the effects of farmer managed natural regeneration practice on some selected livelihoods including, household income, values of tree products, crop production, and food security among the different categories of households.

The study showed that FMNR is practiced almost everywhere as most of the households have a good knowledge of the technique; it is more the degree of the practice that varies.

The results also indicate that keeping, protecting and managing trees in the farmland have significant effects on the livelihoods of the rural poor in the Sahelian and Sudano-Sahelian countries of West Africa Sahel. In fact, it has been shown that if an average household in the Sahel were to decide to practice FMNR continuously, it would result in an increase in gross income by US$ 72 per year. In other words, if a number of 1000 households in a community were to decide to practice the farmer managed natural regeneration continuously, this will result in an increase of the gross income of that community of US$ 72,000 per year.

Noticeable changes can also be observed on the value of tree products. According to the results, if an average low practitioner of FMNR were to become a continuous practitioner, it would lead to a significant increase in the value of the products harvested from trees by about 36 % in Burkina Faso, 38 % in Mali, 36 % in Niger and 34 % in Sahel as the whole: indicating additional gains of \$32 ha^{-1} in Burkina Faso, \$60 ha^{-1} in Mali, \$76 ha^{-1} in Niger as well as Senegal.

These results also lend support to the household resilience hypothesis of farmer managed natural regeneration. In other words; farmers who actively practice the farmer managed natural regeneration are more likely to avoid periods of food insecurity as it positively affects their ability to cope with shocks such as drought and flood. The results from this study suggest that if an average farmer managing natural regeneration at a low level was to become a new manager of natural regeneration this will result to a significant increase of the dietary diversity (as captured through the food consumption score) by about 14 % in Burkina Faso, 13 % in Mali, 10 % in Niger, 13 % in Senegal and 12 % in the Sahel globally.

The main conclusion stemming from this study is that the practice of FMNR can provide significant benefits to rural households and thus improve their livelihood in terms of income and food security. It can also play a crucial role in aiding economic development at the community level. However, several factors such as uncontrolled cutting of trees, animal damage, and lack of tree germplasm in the soil impede the regeneration of trees on farms. Farmers also reported institutional and policy constraints whereby many farmers noted the unreasonable forest codes as a limiting factor and heavy-handedness on the part of forest officers.

To foster the widespread dissemination and enhance the capacity of farmers to increase, diversify and sustain tree-based production systems, an enabling institutional, technical and policy environment needs to be promoted.

Re-enforcing and developing the capacities of existing local institutions dealing with the management of natural resource in general and more specifically forest/agroforestry resources is needed to support institutional arrangement for joint forestry management.

Finally, a platform for dialogue between technicians originating from the various departments in charge of forestry resources management and among local leaders can be an avenue to design optimal and efficient formal institutions and institutional arrangements to manage land and trees that can overcome threats to tree resources and also motivate better management of trees.

Acknowledgments The authors are grateful to the International Funds for Agricultural Development (IFAD) through the Free University of Amsterdam, the United States Agency for International Development (USAID) who provided financial support for this study. The INERA, IER, INRAN and ISRA were invaluable resources during the collection of the field data. Finally, we indebted to the thousands of households from rural communities in Burkina Faso, Mali, Niger Republic, and Senegal, whose experience, knowledge, perseverance, and friendship provided the foundation for our understanding and interpretations. We are also thankful to John Weber and Judith Oduol for their constructive comments and suggestions which helped improve an earlier draft of this paper. We definitely wish to thank the two anonymous reviewers and the editor who provided very insightful comments and suggestions that helped strengthen our manuscript.

Appendix: Methodology used to classify farmer managed natural regeneration groups

Five different sets of variables were collected during the survey to help categorizing farmers in different group according to their level of implementing farmer managed natural regeneration practice.

Ownership of farmland This information was collected to capture whether or not the household owns a farmland and also the total size of his farmland was estimated

Tenure arrangement Because the preservation of and care for naturally regenerated trees on farm as well as deliberate tree planting can be influenced by the tenure arrangement, the surveys tempted to capture information on tenure arrangement. A summary of tenure arrangement and related rights is provided in the table below:

Tenure arrangement	Rights
Inheritance	Full rights (access, withdrawal, management, exclusion, alienation). After the death of the family founder, the field commonly used by the family is passed to the children. The land is divided on the basis of the existing law. Each married male heir becomes a head of his household and of the share of land he inherited
Purchase	Full rights (access, withdrawal, management, exclusion, alienation). All ‘bundles of rights’ to the land, including exclusion and alienation, are sold from the land owner to the buyer. The buyer becomes owner of the land
Lease	Access, limited withdrawal and management rights (in accordance with Owner). The land is transferred in exchange for either money or any other ‘security deposit’. It remains at any time the property of the initial owner who holds exclusive alienation rights. The person leasing has certain management and usage rights. This tenure arrangement is valid as long as the deposit is not repaid
Loan (temporary borrowing)	The land is loaned for a temporary or undefined period, without any security deposit or monetary transaction. Borrowed land stays at any time the property of the initial owner who holds exclusive alienation rights. The land may at any time be resumed by the owner

Adapted from Mikulcak (2011)

Based on this it is obvious that household under lease and loan tenure arrangement are less likely to practice farmer managed natural regeneration.

Awareness/knowledge of FMNR practices Because a new practice or a technology cannot be adopted if someone is unaware or has no knowledge of it we also attempt to capture the level of awareness and knowledge of the respondent on FMNR practices. A score (score 0 for poor knowledge to 10 for a very good knowledge) was then affected to each farmer based on the answers they provided with regard to the technical itinerary follows while practicing the FMNR

FMNR in practice
1. FMNR depends on the existence of living tree stumps in the fields to be revegetated. New stems which can be selected and pruned for improved growth sprout from these stumps. Standard practice has been for farmers to slash this valuable re-growth each year in preparation for planting crops
2. With a little attention, this growth can be turned into a valuable resource, without jeopardizing, but in fact, enhancing crop yields. Here, all stalks except one have been cut from the stump. Side branches have been pruned half way up the stem. This single stem will be left to grow into a valuable pole. The problem with this system is that when the stem is harvested, the land will have no tree cover and there will be no wood to harvest for some time
3. Much more can be gained by selecting and pruning the best five or so stems and removing the remaining unwanted ones. In this way, when a farmer wants wood she can cut the stem(s) she wants and leaves the rest to continue growing. These remaining stems will increase in size and value each year, and will continue to protect the environment and provide other useful materials and services such as fodder, humus, habitat for useful pest predators, and protection from the wind and shade. Each time one stem is harvested, a younger stem is selected to replace it
Trees that do not hinder crop growth are the most acceptable species for farmer managed natural regeneration (FMNR).

Tree diversity The important determinants of which species to use will be: whatever species are locally available with the ability to re-sprout after cutting, and the value local people place on those species. It is expected that a farmer practicing natural regeneration must normally keep and manage on farm a big proportion of dominant trees found in the parklands within the village. This variable was captured by identifying in each farmer's field the different tree species natural regenerated and managed.

Tree density The density of trees managed on farm is an important indicator of the level of intensity of FMNR practices. This was done thoroughly by collecting information from each plot on the number of trees/size kept and managed by the farmer. The parameters collected from each plot were the diameter at breast in cm as well as the number of trees. To differentiate the very young, young, mature, old and very old trees, the number of trees/farm was summarized according to five different sizes as follows:

Households ID	Diameter <10 cm	Diameter (10–20 cm)	Diameter (20–40 cm)	Diameter (40–60 cm)	Diameter >60 cm
i	n_{i1}	n_{i2}	n_{i3}	n_{i4}	n_{i5}

Since it is possible to establish a relationship between the diameter at breast and the age of tree (Loewenstein et al. 2000; Lukaszkiewicz and Kosmala 2008), the diameter was used as a proxy of the age of trees as it was not possible to get suitable information on age.

Based on the number of trees with different size and that of the farm, it was able to obtain the density of trees in each farmland. Different cutoff levels for low, medium and high density were then used to reflect differences in parkland systems.

This led us finally to evaluate the regeneration index (RI) needed to categorize farmers according to their level of implementation of FMNR.

The regeneration index $\mathrm{RI}_i = \frac{\sum_{j=1}^{2} n_{ij}}{\sum_{j=3}^{5} n_{ij}}$; $i \neq j$ and $\mathrm{j} = 1\ldots,5$. n_{ij} is the total number of trees on farm with different diameters, kept and managed by a farmer.

Decision rule $\mathrm{RI}_i = 1$ indicates that the farmland is equitably populated with trees of different sizes including very young and old trees leading to the conclusion that, we are dealing with a continuous practitioner of farmer managed natural regeneration.

In other words, a continuous practitioner of farmer managed natural regeneration is a farmer who: (1) owns at least one farmland under a given tenure arrangement (in most case inherited or purchased); (2) has a good or very good knowledge of the practice; (3) keeps and manages at least 70 % of the dominants tree species generally found in many parklands within the village/community; (4) belongs to the category of farmers with a regeneration index equal to one ($R = 1$).

$RI_i < 1$ indicates that the farmland is mainly dominated by old trees dealing with the conclusion that we are dealing with a low practitioner of farmer managed natural regeneration.

As such, a low practitioner of farmer managed natural regeneration is a farmer who: (1) owns at least one farmland under a given tenure arrangement (in most case inherited or purchased); (2) has a good or very good knowledge of the practice; (3) keeps and manages at least 70 % of the dominants tree species generally found in many parklands within the village/community; (4) belongs to the category of farmers with a regeneration index less than one (RI < 1).

$RI_i > 1$ indicates that the farmland is mainly dominated young trees indicating that we are dealing with a young practitioner of farmer managed natural regeneration.

This indicates that a young practitioner of farmer managed natural regeneration is a farmer who: (1) owns at least one farmland under a given tenure arrangement (in most case inherited or purchased); (2) has a good or very good knowledge of the practice; (3) keeps and manages at least 70 % of the dominants tree species generally found in many parklands within the village/community; (4) belongs to the category of farmers with a regeneration index greater than one (RI > 1).

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