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Divergent reactivity of alk-5-ynylidenecyclopropanes in the presence of the 1st or the 2nd generation Grubbs' catalysts

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Abstract

Alk-5-ynylidenecyclopropanes, by virtue of being equipped with a strained cyclopropane system, can be divergently elaborated into bicyclo[3.3.0]octenes or exocyclopropylidenecycloalkenes depending on whether they react with the first or the second generation Grubbs' ruthenium carbenes. While the highly reactive second generation system catalyses the formation of ring-closing metathesis products, the less [metathesis] active first generation carbene promotes an intramolecular [3 + 2] cycloaddition to give the bicarbocyclic skeletons.

Keywords: Alkylidenecyclopropanes; Ruthenium; Metathesis; Cycloaddition

1. Introduction

The development of air-stable well-defined carbene ruthenium catalysts which exhibit high activity and wide functional group tolerance in olefin metathesis has had a profound impact in the field of synthetic chemistry [1]. Research efforts in this area have been primarily focused on diene ring-closing and cross metathesis processes, while metal carbene-catalyzed enyne metathesis reactions, particularly ring closing processes, have received less attention [2].

Nevertheless, in recent years, numerous examples of ring-closing enyne metatheses (RCM) have been reported. For instance, it has been shown that the first generation Grubbs ruthenium carbene complex **1** catalyzes the cycloisomerization of **3a** into **4a** in 90% yield. Remarkably, this complex fails to induce the RCM of the 1,1-disubstituted alkene **3b**. However, this transformation can be achieved upon treatment with the more active second generation catalyst **2**, which contains a N-heterocyclic carbene ligand instead of one PCy_3[3] (see Scheme 1).

On the other hand, several studies have shown that the above ruthenium carbenes can also induce non-metathetical transformations, such as the Kharasch addition [4], olefin isomerizations [5], or hydrogenations [6]. These reactions are most probably promoted by ruthenium species different from the initial carbenes, which are generated in situ [7]. In this context, we have recently reported that treatment of alk-5-ynylidenecyclopropanes **5** with catalytic amounts of the "first generation" Grubbs' complex **1**, instead of producing the expected RCM diene **7**, leads majoritarily to the bicyclic adducts **6**, which results from an intramolecular [3 + 2] cycloaddition reaction [8] (see Scheme 2).

Herein, we describe our recent investigations into the reactivity of alk-5-ynylidenecyclopropanes **5** upon treatment with different ruthenium carbene catalysts, and demonstrate that in contrast to **1**, the second generation Grubbs' complex **2** does promote the ring-closing metathesis reaction to give cycloalkenes containing conjugated exo-cyclopropylidene moieties.

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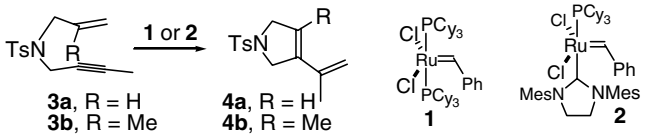
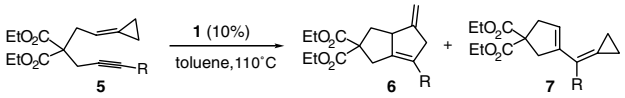


Scheme 1.

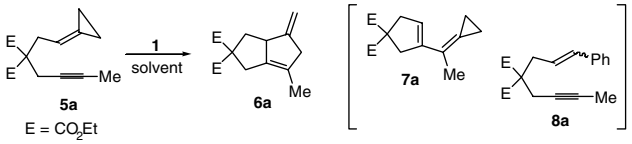


Scheme 2.

2. Results and discussion

The impetus for this study arose from interest in obtaining substituted allylidenecyclopropane derivatives, a type of compounds of theoretical and synthetic relevance that have surprisingly received scant attention, most probably due to the absence of practical methods for their assembly [9]. We envisaged that the ring-closing metathesis of alk-5-ynylidenecyclopropanes such as **5**, which can be readily prepared from commercial compounds [10], might lead to 1-(1-cyclopropylidenealkyl)cyclopentenes such as **7**, a skeletal framework that, to the best of our knowledge, has not been previously synthesized.

Quite surprisingly, treatment of enyne **5a** [11] with the well-known Ru-benzylidene **1** (20 mol%) under standard metathesis conditions (CH_2Cl_2, 40 °C) gave only trace amounts of the expected ring-closing metathesis product (**7a**), with the major compound isolated being the cyclopentene adduct **6a** (36% yield, see Scheme 3 and Table 1, entry 1). Although we had previously reported that enynes such as **5**, which bear a methylencyclopropane end group, undergo efficient intramolecular [3 + 2] cycloaddition processes in the presence of palladium catalysts [12], we would not have expected that a carbenic ruthenium could also induce such annulation reactions.



Scheme 3.

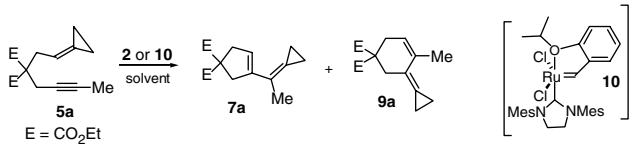
Table 1
Ruthenium-catalyzed intramolecular [3 + 2] cycloaddition of **5a**[a]

Entry	Mol% **1**	Solvent (mM)	*T* (°C)	Time	Yield (**6a**)[b]
1	20	CH_2Cl_2 (10)	40	2 h	36%
2	20	$Cl_2(CH_2)_2$ (10)	84	4 h	43%
3	20	Toluene (10)	30	4 h	–
4	20	Toluene (10)	110	4 h	59%
5	**10**	**Toluene (100)**	**110**	**45 min**	**78%**
6	5	Toluene (100)	110	3 h	54%[c]
7	2	Toluene (100)	110	3 h	34%[d]

[a] The synthesis of the substrates **5** is described in the supplementary information.
[b] Isolated yield.
[c] 73% based on recovered starting enyne.
[d] 75% based on recovered starting enyne.

The novelty of the non-metathetic behavior of **1**, prompted us to investigate further the scope and limitations of the process. Careful checking of the composition of the above Ru-catalyzed reaction showed that in addition to the cycloadduct **6a** and traces of the diene **7a** (less than 5%), we could also detect a small amount of the cross-metathesis enyne **8a** (less than 10%). As shown in Table 1, performing the reaction in 1,2-dichloroethane at 80 °C afforded a slight improvement in yield of the desired cycloadduct (43%; entry 2), while refluxing in toluene provided **6a** in 59% yield (65% based on recovered starting material; entry 4). Remarkably, increasing the substrate concentration had a substantial impact on the efficiency of the cycloaddition reaction. Heating a 0.1 M solution of **5a** in toluene at 110 °C in the presence of 10% of carbene complex **1** led to total consumption of the starting enyne and provided a 78% yield of the desired cycloadduct (entry 5).

Interestingly, and in contrast to the outcome obtained when the cyclopropane-containing enyne **5a** is treated with the first generation Grubbs' catalyst, reaction of **5a** with **2** (10 mol%) in CH_2Cl_2 at room temperature led to the formation of **7a**, which results from a ring closing metathesis reaction, as the major product (isolated in a 25% yield, see Scheme 4). In addition to this product and partial recovery of starting material, we could also observe the formation of an isomeric cyclopropyldiene derivative that could be identified as the cyclohexene **9a** (isolated in 17% yield). The cycloadduct **6a** was also detected in the reaction mixture, albeit it was formed only in trace amounts. As shown in Table 2, the reaction is more efficient when carried out in toluene, providing



Scheme 4.

Table 2
Ruthenium-catalyzed ring-closing metathesis of **5a**

Entry	[Ru] (mol%)	Solvent (mM)	*T* (°C)	Time	Yield (**7a**)[a]	Yield (**9a**)[a]
1	**2** (10)	CH_2Cl_2 (10)	22	6 h	25%[a]	17%[b]
2	**2** (10)	Toluene (10)	22	5 h	45%	34%
3	**2** (10)	Toluene (10)	110	30 min	47%	37%
4	**10** (10)	Toluene (10)	22	15 min	46%	34%
5	**10** (20)	CH_2Cl_2 (10)	22	6 h	23%[b]	15%[b]

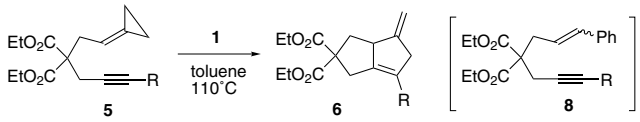
[a] Isolated yields.
[b] Part of starting material was recovered.

the products in 79% overall yield, and, although it can be carried out at room temperature, it is much faster when kept under reflux (entry 3, 84% yield). Using 5 mol% of the catalyst instead of 10 mol% leads to partial recovery of the starting material even after refluxing for 7 h. Interestingly, use of Hoveyda-Grubbs's carbene **10** instead of **2** leads to similar yields and proportions of the dienic products but the reaction proceeds considerably faster (entries 4, Table 2).

Therefore, from the results described above it can be deduced that ruthenium carbene metathesis complexes present a ligand-dependent dichotomy with regard to their reactivity with alkynylidenecyclopropane **5a** in that it behaves as a bipotential substrate whose reactivity with ruthenium carbenes can be modulated using different ligands on the metal [13].

With these results at hand we next investigated the effect of the substitution at the alkyne terminus on both the cycloaddition and the cyclization processes. With regard to the cycloaddition outcome (see Scheme 5, Table 3), it can be observed that the reaction is slightly more sluggish when the alkyne bears substituents bulkier than methyl, and is even inhibited in the case of the TMS-alkynyl derivative **5g**, a result which contrasts with that obtained in the case of the Pd-mediated annulation [12]. It should be noted that in all these cases the minor reaction products included traces of the cross metathesis enynes **8**.

In Table 4, we summarize the results observed when the yncyclopropylidenes are treated with the 2nd generation Grubbs' catalyst **2** in toluene at reflux (see Scheme 6). As can be deduced from the table, changes in the alkyne substituent have a notable influence in the proportion of the RCM isomeric products **7** and **9**. Therefore, replacing the methyl by a *t*-butyldimethylsilyloxymethyl group conveys the majoritary formation of the cyclopentenic product. Interestingly, the unprotected substrate **5f** failed to participate in the metathesis reaction, leading to recovery of the starting material. The cyclization also proceeds with the alkyne-unsubstituted substrate **5b**, to give primarily the cyclopentenyl adduct **7b**. As in the case of the cycloaddition reaction, the TMS bearing substrate **5g**, remained mostly unaltered upon prolonged heating with the catalyst.

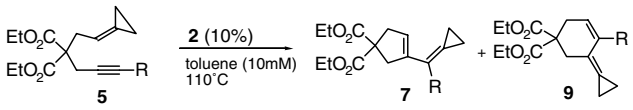


Scheme 5.

Table 3
Effect of alkyne substituent on the Ru-catalyzed intramolecular cycloaddition of **5**

Entry	R (substrate)	[Ru] (%)	Solvent (mM)	Time (min)	Yield of **6**
1	CH_3 (**5a**)	10	Toluene (10)	45	78% (**6a**)
2	H (**5b**)	10	$(CH_2)_2Cl_2$ (10)	240	47%[a] (**6b**)
3	CH_2CH_3 (**5c**)	10	Toluene (10)	300	56% (**6c**)
4	CH_2CH_3 (**5c**)	15	Toluene (10)	90	73% (**6c**)
5	$(CH_2)_4CH_3$ (**5d**)	15	Toluene (100)	120	67% (**6d**)
6	CH_2OTBS (**5e**)	15	Toluene (10)	205	62% (**6e**)
7	CH_2OH (**5f**)	10	Toluene (100)	300	26% (**6f**)
8	$SiMe_3$ (**5g**)	10	Toluene (100)		–

[a] This reaction was carried out in refluxing dichloroethane; in toluene at 110 °C we observed several decomposition products and obtained lower yields of the cycloadduct.



Scheme 6.

Table 4
Effect of alkyne substituent on the Ru-catalyzed RCM of **5**

Entry	R (substrate)	Time (min)	Yield (**7**)[a]	Yield (**9**)[a]
1	CH_3 (**5a**)	30	47%	37%
2	CH_2CH_3 (**5c**)	60	30%	39%
3	CH_2OTBS (**5e**)	60	43%	<5%
4	CH_2OH (**5f**)	300	–[c]	–[c]
5	H (**5b**)	90	~53%[b]	–[c]
6	$SiMe_3$ (**5g**)	300	–[c]	–[c]

[a] Isolated yields.
[b] The compound is contaminated by other minor products with similar chromatographic properties.
[c] Not detected.

From the data above, it can be concluded that changing the alkyne substituent does not alter the intrinsic tendency of the first and second generation ruthenium carbenes to give either the [3 + 2] cycloadducts or the RCM products, albeit in both cases we observed that bulkier substituents slow down the reactions, and in the case of the RCM, they influence the ratio of the isomeric products **7** and **9**.

From the mechanistic point of view, the different behaviour of both ruthenium carbenes could be interpreted in terms of their different metathetic capability, however the ability of **1** to induce the cycloaddition reaction might be a consequence of its greater propensity to decompose into other ruthenium species that could be responsible for catalyzing the cycloaddition [14]. Since we have found that preheating of a solution of **1** in toluene (2 h, 110 °C) prior to addition of the substrate inhibits the cycloaddition reaction completely, it can be deduced that such active species are not thermolyzed derivatives of **1** [15]. On the other hand we could demonstrate, by ^{31}P NMR, that adding enyne **5a** at room temperature to a solution of **1** (10 mol%) in CD_2Cl_2 leads to a relatively rapid disappearance of its characteristic singlet at 37.2 ppm, along with the

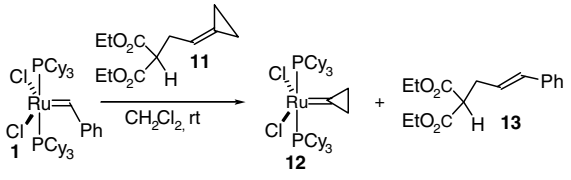
simultaneous appearance of a new ^{31}P signal at 31.8 ppm, with complete conversion within 1 h [16].

Since the ^{1}H NMR spectrum of this reaction mixture revealed the presence of a small amount of the cross-metathesis product **8a** (approx. 10%) together with unaltered starting enyne **5a**, we inferred that the new ^{31}P signal was due to the cyclopropylidene ruthenium carbene **12**. This conclusion was supported by observation of the same signal in the ^{31}P NMR spectrum of the residue of the cross metathesis reaction between alkylidenecyclopropane **11** and carbene **1** (Scheme 7) [17].

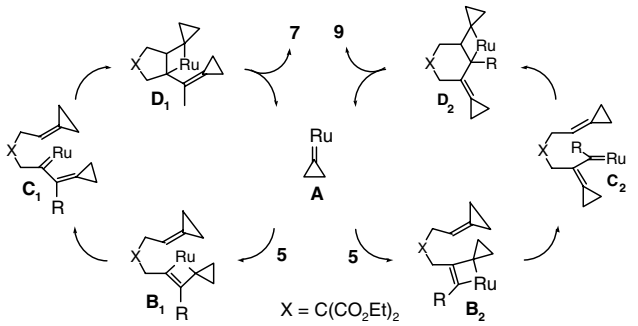
Although all attempts to crystallize **12** failed, the NMR characteristics of the brown solid obtained by precipitation of this residue with pentane are consistent with this cyclopropylcarbene (**12**) being the major component. Interestingly, heating enyne **5a** under reflux in toluene for 45 min in the presence of **12** (approx. 10 mol%) provided the bicyclo[3.3.0]octane adduct **6a** in 82% yield. These observations suggest that the cyclopropylcarbene **12** could be the actual (pre)catalyst of the cycloaddition, although catalysis by a ruthenium species directly generated from **1** in the presence of the enyne cannot be ruled out completely. Since preheating a solution of **12** in toluene at 70 °C for 45 min generated a catalytically inactive residue, it seems that the specific ruthenium species that is immediately responsible for the cycloaddition must be generated in situ from **12** in the presence of the substrate.

Recently, we have demonstrated that the cycloaddition reaction can be catalyzed by non-carbenic ruthenium complexes [8]. Therefore heating **5a** under reflux in toluene in the presence of 10 mol% of $Cp^{*}Ru(CH_3CN)_3PF_6/Et_4NCl$ or $(Indenyl)Ru(PPh_3)_2Cl$ gave the desired adduct in 11% and 18% yield, respectively. The best yields (35%, 77% based on recovered enyne) were obtained in presence of $Cl_2Ru(PPh_3)_3$ (10%). These results seem to reinforce the hypothesis that the cycloaddition reaction is promoted by a non-carbene ruthenium species generated under the reaction conditions and that, presumably, it occurs by a different mechanism than in the case of palladium.

With regard to the RCM, the most reasonable mechanistic scenario might involve first the generation of the cyclopropylruthenium carbene **A** (Scheme 8, the ligands of the ruthenium are not indicated) which, most probably, is the active propagating species. This carbene undergoes a [2 + 2] cycloaddition reaction with the alkyne moiety to give either regioisomer $\mathbf{B}_1$ or $\mathbf{B}_2$. Ring opening of the ruthenacyclobutene would produce carbenes $\mathbf{C}_1$ or $\mathbf{C}_2$, and subsequent intramolecular [2 + 2] cycloaddition followed by ring opening yields the reaction products **7** or **9**, with regeneration of the active ruthenium catalyst.



Scheme 7.



Scheme 8.

3. Conclusions

1-Cyclopropylidene-5-alkynyl systems, by virtue of ring strain of the cyclopropyl ring, are particularly rich substrates in terms of chemical reactivity and versatility. Treatment of these compounds with the second generation Grubbs' carbene complex allows for unmasking of their intrinsic ring closing metathesis reactivity to produce interesting and otherwise difficult to prepare conjugated allylcyclopropylidene systems. On the other hand, reaction with the first generation ruthenium catalyst promotes a [3 + 2] cycloaddition reaction to produce bicarbocyclic [3.3.0] systems.

Current work is focused on further investigating the mechanism of the cycloaddition reaction as well as on studying the reactivity of the cyclopropyldienes obtained in the ring closing metathesis reactions.

4. Experimental

4.1. General details

All dry solvents were freshly distilled under argon from an appropriate drying agent before use. Grubbs catalysts were purchased from Aldrich and used without further purification. Their purity was determined by NMR to be higher than 98%. All reactions were conducted in dry solvents under argon atmosphere unless otherwise stated. Concentrations were carried out under vacuum in a rotavap. Flash chromatography was carried out in silica gel unless otherwise stated. ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$, at 250 and 62.9 MHz, respectively, and in some cases at 300 or 500 MHz (75.461 or 125.7 for ^{13}C). Carbon types were

determined from DEPT-NMR experiments. ^{31}P NMR spectra were recorded in a Varian spectrometer at 121.47 MHz. Mass spectra were acquired using a Chemical Ionization technique or ESI-TOF techniques registering on a BIOTOF II (Bruker). GC–MS was carried out using the Agilent Technologies 6896N, Network GC System, equipped with the HP 190915-433 column and the Agilent 5976 Network Mass Selective Detector switched to the Chemical Ionization Mode.

4.2. Procedure for the Ru-catalyzed [3 + 2] cycloaddition of **5** (exemplified for the synthesis of **6a**)

Compound **5a** (60 mg, 0.210 mmol) and ruthenium carbene **1** (18 mg, 0.021 mmol) were dissolved in toluene (2.0 mL) and heated under reflux during 45 min. The solvent was concentrated and the crude residue was chromatographed (0–2% Et_2O/hexanes) to afford 47 mg of bicycle **6a** as a colorless oil.

4.2.1. Diethyl-6-(methyl)-4-methylene-1,2,3,3a,4,5-hexahydro-2,2-pentalenedicarboxylate (**6a**)

^1H NMR δ (ppm): 4.82 (1H, br s), 4.78 (1H, br s), 4.20–4.13 (4H, m), 3.58–3.49 (1H, m), 3.41–3.33 (1H, m), 2.95–2.82 (2H, m), 2.73–2.64 (1H, m), 2.57 (1H, dd, $J = 12.6$ and 7.7 Hz), 1.75 (1H, dd, $J = 12.6$ and 11.0 Hz), 1.62 (3H, s), 1.27–1.19 (6H, m). ^{13}C NMR δ (ppm): 172.4 (CO), 171.8 (CO), 152.7 (C), 140.1 (C), 127.8 (C), 106.2 (CH_2), 63.1 (C), 61.5 (CH_2), 61.4 (CH_2), 53.9 (CH), 48.0 (CH_2), 37.9 (CH_2), 31.7 (CH_2), 14.2 (CH_3), 14.1 (CH_3), 14.0 (CH_3). MS: 279 (M + 1, 58%), 205 (M-CO_2Et, 100%) HRMS: calculated for $C_{16}H_{23}O_4$ 279.1596, found 279.1602.

4.2.2. Diethyl 4-methylene-1,2,3,3a,4,5-hexahydro-2,2-pentalenedicarboxylate (**6b**)

^1H NMR δ (ppm): 5.37 (1H, br s), 4.89 (1H, br s), 4.83 (1H, br s), 4.24–4.13 (4H, m), 3.61–3.51 (1H, m), 3.43–3.31 (1H, m), 3.18–3.04 (1H, m), 2.99–2.78 (2H, m), 2.62 (1H, dd, $J = 12.6$ and 7.7 Hz), 1.79 (1H, dd, $J = 12.6$ and 11.1 Hz), 1.28–1.20 (6H, m). ^{13}C NMR δ (ppm): 172.3 (CO), 171.7 (CO), 152.9 (C), 148.3 (C), 118.7 (CH), 106.7 (CH_2), 63.0 (C), 61.5 (CH_2), 61.4 (CH_2), 53.5 (CH), 43.6 (CH_2), 37.6 (CH_2), 32.3 (CH_2), 14.0 (CH_3). MS: 265 (M + 1, 18%). HRMS: calculated for $C_{15}H_{21}O_4$265.1440, found 265.1437.

4.2.3. Diethyl-6-(ethyl)-4-methylene-1,2,3,3a,4,5-hexahydro-2,2-pentalenedicarboxylate (**6c**)

^1H NMR δ (ppm): 4.83 (1H, s), 4.79 (1H, s), 4.23–4.11 (4H, m), 3.58–3.51 (1H, m), 3.37 (1H, d, $J = 18.9$ Hz), 3.05–2.87 (2H, m), 2.75–2.67 (1H, m), 2.56 (1H, dd, $J = 12.6$ and 7.7 Hz), 2.16–1.94 (2H, m), 1.75 (1H, dd, $J = 12.6$ and 11.0 Hz) 1.27–1.19 (6H, m), 0.99 (3H, t, $J = 7.4$ Hz). ^{13}C NMR δ (ppm): 172.3 (CO), 171.8 (CO), 152.6 (C), 139.0 (C), 133.3 (C), 106.1 (CH_2), 63.0 (C), 61.5 (CH_2), 61.4 (CH_2), 54.0 (CH), 45.4 (CH_2), 37.6 (CH_2), 31.8 (CH_2), 22.3 (CH_2), 14.0 (CH_3), 12.5 (CH_3). MS: 293 (M + 1, 7%). HRMS: calculated for $C_{17}H_{24}O_4$ 292.1675, found 292.1671.

4.2.4. Diethyl-6-(pentyl)-4-methylene-1,2,3,3a,4,5-hexahydro-2,2-pentalenedicarboxylate (**6d**)

^1H NMR δ (ppm): 4.84 (1H, s), 4.80 (1H, s), 4.24–4.15 (4H, m), 3.60–3.54 (1H, m), 3.38 (1H, d, $J = 19.1$ Hz), 3.03–2.83 (2H, m), 2.73 (1H, d, $J = 16.5$ Hz), 2.62–2.56 (1H, m), 2.10–1.98 (2H, m), 1.78–1.62 (1H, m), 1.44–1.21 (12H, m), 0.96–0.89 (3H, m). ^{13}C NMR δ (ppm): 172.4 (CO), 171.8 (CO), 152.7 (C), 139.8 (C), 132.1 (C), 106.1 (CH_2), 63.0 (C), 61.5 (CH_2), 61.4 (CH_2), 53.9 (CH), 45.8 (CH_2), 37.7 (CH_2), 31.9 (CH_2), 31.6 (CH_2), 29.1 (CH_2), 27.4 (CH_2), 22.4 (CH_2), 14.0 (CH_3). MS: 335 (M + 1, 19%). HRMS: calculated for $C_{20}H_{30}O_4$ 334.2144, found 334.2154.

4.2.5. Diethyl-6-(tertbutyldimethylsilyloxymethyl)-4-methylene-1,2,3,3a,4,5-hexahydro-2,2-pentalene dicarboxylate (**6e**)

^1H NMR δ (ppm): 4.89 (1H, br s), 4.82 (1H, br s), 4.23–4.00 (6H, m), 3.59–3.31 (2H, m), 3.12–1.98 (2H, m), 2.87–2.75 (1H, m), 2.57 (1H, dd, $J = 12.6$ and 7.9 Hz), 1.75 (1H, dd, $J = 12.6$ and 11.1 Hz), 1.24 (6H, q, $J = 6.6$ Hz), 0.88 (9H, s), 0.04 (6H, s). ^{13}C NMR δ (ppm): 172.3 (CO), 171.6 (CO), 151.8 (C), 141.5 (C), 130.6 (C), 106.6 (CH_2), 63.1 (C), 61.5 (CH_2), 60.7 (CH_2), 54.4 (CH), 44.0 (CH_2), 37.3 (CH_2), 32.0 (CH_2), 25.9 (CH_3), 18.3 (C), 14.0 (CH_3), −5.3 (CH_3), −5.4 (CH_3). MS: 409 (M + 1, 1%), 282 (16%), 115 (65%), 75 (100%). HRMS: calculated for $C_{22}H_{37}O_5Si$ 409.2410, found 409.2418.

4.2.6. Diethyl-6-(hydroxymethyl)-4-methylene-1,2,3,3a,4,5-hexahydro-2,2-pentalenedicar boxylate (**6f**)

^1H NMR δ (ppm): 4.88 (1H, br s), 4.81 (1H, br s), 4.21–4.01 (6H, m), 3.70–3.40 (2H, m), 3.17–2.97 (2H, m), 2.74 (1H, br s), 2.64 (1H, dd, $J = 12.6$ and 7.9 Hz), 2.01 (1H, br s), 1.75 (1H, dd, $J = 12.6$ and 11.0 Hz), 1.21 (6H, q, $J = 6.9$ Hz). ^{13}C NMR δ (ppm): 172.0 (CO), 171.8 (CO), 151.7 (C), 143.1(C), 130.9 (C), 106.9 (CH_2), 62.7 (C), 61.6 (CH_2), 61.5 (CH_2), 59.8 (CH_2), 53.9 (CH), 43.7 (CH_2), 37.2 (CH_2), 32.0 (CH_2), 14.0 (CH_3). MS: 295 (M + 1, 26%), 279 (M-OH, 42%), 235 (50%), 61 (100%). HRMS: calculated for $C_{16}H_{23}O_5$ 295.1545, found 295.1540.

4.3. Procedure for the Ru-catalyzed ring-closing metathesis of **5** (exemplified for **5a**)

Compound **5a** (50 mg, 0.180 mmol) and ruthenium carbene **2** (15.3 mg, 0.018 mmol) were dissolved in toluene (18 mL), and the mixture heated under reflux during 30 min. The solvent was removed under vacuum

and the crude residue was chromatographed (1–3% Et_2O/hexanes) to afford 23.5 mg of the ring-closing metathesis product **7a** as a colorless oil and 18.5 mg of an isomeric cyclopropyldiene derivative **9a** as a colorless oil.

*4.3.1. Diethyl-3-(1-cyclopropylidene-ethyl)-cyclopent-3-ene-1,1-dicarboxylate (**7a**)*

^{1}H NMR δ (ppm): 5.49 (1H, s), 4.18 (4H, q, $J = 7.1$ Hz), 3.29 (2H, s), 3.08 (2H, s), 1.94 (3H, s), 1.33–1.28 (2H, m), 1.23 (6H, t, $J = 7.1$ Hz), 1.02 (2H, t, $J = 7.2$ Hz). ^{13}C NMR δ (ppm): 172.6 (CO), 142.2 (C), 122.1 (C), 120.9 (CH), 120.7 (C), 61.9 (CH_2), 59.2 (C), 41.4 (CH_2), 40.8 (CH_2), 19.0 (CH_3), 14.2 (CH_3), 5.6 (CH_2), 1.3 (CH_2). HRMS (ESI-TOF): calculated for $C_{16}H_{22}NaO_4$ 301.1416, found 301.1410.

*4.3.2. Diethyl-5-cyclopropylidene-4-methyl-cyclohex-3-ene-1,1-dicarboxylate (**9a**)*

^{1}H NMR δ (ppm): 5.51 (1H, s), 4.19 (4H, q, $J = 6.9$ Hz), 2.97 (2H, s), 2.68 (2H, s), 1.90 (3H, s), 1.34–1.18 (10H, m). ^{13}C NMR δ (ppm): 171.2 (CO), 133.4 (C), 121.9 (C), 121.2 (CH), 119.9(C), 61.2 (CH_2), 54.1 (C), 35.9 (CH_2), 31.4 (CH_2), 20.0 (CH_3), 14.0 (CH_3), 5.4 (CH_2), 0.2 (CH_2). HRMS (ESI-TOF): calculated for $C_{16}H_{22}NaO_4$ 301.1416, found 301.1410.

*4.3.3. Diethyl-3-cyclopropylidenemethyl-cyclopent-3-ene-1,1-dicarboxylate (**7b**)*

^{1}H NMR δ (ppm): 6.52 (1H, s), 5.49 (1H, s), 4.20 (4H, q, $J = 7.1$ Hz), 3.26 (2H, s), 3.08 (2H, s), 1.26–1.23 (8H, m), 1.10–1.07 (2H, m). ^{13}C NMR δ (ppm): 172.3 (CO), 140.2 (C), 125.3 (C), 123.6 (CH), 114.8 (CH), 61.5 (CH_2), 59.0 (C), 40.6 (CH_2), 29.7 (CH_2), 14.0 (CH_3), 3.8 (CH_2), 1.6 (CH_2). HRMS (ESI-TOF): calculated for $C_{15}H_{20}NaO_4$ 287.1259, found 287.1254.

*4.3.4. Diethyl-3-(1-cyclopropylidene-propyl)-cyclopent-3-ene-1,1-dicarboxylate (**7c**)*

^{1}H NMR δ (ppm): 5.51 (1H, s), 4.18 (4H, q, $J = 7.1$ Hz), 3.30 (2H, s), 3.08 (2H, s), 2.37 (2H, q, $J = 7.5$ Hz), 1.26–1.21 (8H, m), 1.11–1.06 (5H, m). ^{13}C NMR δ (ppm): 172.4 (CO), 140.9 (C), 126.1 (C), 120.8 (C), 120.1 (CH), 61.5 (CH_2), 58.8 (C), 41.5 (CH_2), 40.7 (CH_2), 26.3 (CH_2), 14.0 (CH_3), 13.3 (CH_3), 3.9 (CH_2), 1.6 (CH_2). HRMS (ESI-TOF): calculated for $C_{17}H_{24}NaO_4$ 315.1567, found 315.1567.

*4.3.5. Diethyl-5-cyclopropylidene-4-ethyl-cyclohex-3-ene-1,1-dicarboxylate (**9c**)*

^{1}H NMR δ (ppm): 5.51 (1H, s), 4.16–4.12 (4H, m), 2.97 (2H, s), 2.70 (2H, s), 2.30 (2H, q, $J = 7.0$ Hz), 1.33–1.17 (8H, m), 1.03–0.96 (5H, m). ^{13}C NMR δ (ppm): 171.3 (CO), 138.9 (C), 121.0 (C), 119.7 (CH), 118.9 (C), 61.2 (CH_2), 54.1 (C), 36.3 (CH_2), 31.5 (CH_2), 25.7 (CH_2), 14.0 (CH_3), 13.6 (CH_3), 5.6 (CH_2), 0.2 (CH_2). HRMS (ESI-TOF): calculated for $C_{17}H_{24}NaO_4$ 315.1567, found 315.1567.

*4.3.6. Diethyl-3-[2-(tert-butyldimethylsilyloxy)-1-cyclopropylidene-ethyl]-cyclopent-3-ene-1,1-dicarboxylate (**7e**)*

^{1}H NMR δ (ppm): 5.71 (1H, s), 4.44 (2H, s), 4.19 (4H, q, $J = 7.1$ Hz), 3.31 (2H, s), 3.11 (2H, s), 1.26–1.22 (8H, m), 1.14–1.10 (2H, m), 0.88 (9H, s), 0.03 (6H, s) ^{13}C NMR δ (ppm): 172.3 (CO), 138.9 (C), 124.3 (C), 123.8 (C), 121.8 (CH), 64.8 (CH_2), 61.4 (CH_2), 58.6 (C), 41.4 (CH_2), 40.9 (CH_2), 25.9 (CH_3), 18.3 (C), 14.0 (CH_3), 4.0 (CH_2), 1.6 (CH_2), -5.3 (CH_3). HRMS: calculated for $C_{22}H_{37}O_5Si$ 409.2410, found 409.2392.

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Appendix A. Supplementary data

Characterization data and experimental procedures for the synthesis of the alkynylidenecyclopropane precursors **5**. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jorganchem.2005.07.009.

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